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EXHAUST TURBINE AND JET PROPULSION SYSTEMS

By K. Leist and E. Knörnschild

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EXHAUST TURBINE AND JET PROPULSION SYSTEMS*

By K. Leist and E. Knörnschild

PART I. EXHAUST TURBINE AND JET PROPULSION SYSTEMS

By K. Leist

Abstract:

After a short enumeration of the advantages of exhaust turbine and jet propulsion systems over the Otto-cycle engine, there follows a discussion of the possibility of using air flows and very high gas temperatures. Then a series of special power plants, the propulsion of which is produced partly by reaction effect, partly by airscrews propelled by turbines, are compared with each other and with the Otto-cycle engine with respect to power concentration, fuel consumption, weight per unit power, etc.

Outline:

- I. Gas and Blade Temperature
- II. Power Plants Investigated
- III. Fuel Consumption
- IV. Specific Air Consumption
- V. Weight per Unit Power and Its Influence on the Specific Fuel Consumption
- VI. Installation Examples and Concluding Remarks

*"Abgasturbinen und Rückstossertriebwerke." Zentrale für wissenschaftliches Berichtswesen bei der Deutschen Versuchsanstalt für Luftfahrt, E. V., Berlin-Adlershof, Forschungsbericht Nr. 1069, May 15, 1939.

The advantages of gas turbines as main power plants are essentially:

- (1) The absence of oscillating masses; very high rpm's, therefore minimum weight per unit power
- (2) Cheap domestic fuels
- (3) No alternating stresses, limitation of high tensile stresses to few, easily exchangeable parts, thus long life; fewer sources of disturbance, therefore, higher safety of operation
- (4) Lessened fire risk
- (5) No cooling, no ignition installation (except for pulse arrangements)

In addition, there will probably be smaller over-all dimensions, thus diminution of head drag, less noise, easier starting (due to elimination of compression), etc.

I. Gas and Blade Temperature

The reason that installations showing the advantages listed above have not been constructed before now results, above all, from the fact that the admissible gas temperatures which are limited by the occurring blade temperatures were so low that the working process was not sufficiently economical to promise ability of competing with the reciprocating engine.

The investigations performed in the DVL concerning the influence of the gas temperature on the blade temperature of exhaust turbines of various designs brought the result that the partial loading of the turbine rotor with relative-wind air is a suitable means of guaranteeing a safe operating of the turbine even for very high gas temperatures.

For gas temperatures up to 1000°C , exhaust turbines of this type of construction with 50 percent exhaust loading have, partly, completed an operating time of 250 hours and proved good in every respect in the altitude chamber up to 10 kilometers altitude as well as in flight tests up to (for the present) about 8.3 kilometers flight altitude, and in 20-hour-runs at full power. In extensive special investigations of the dependence of the blade temperatures on the gas temperature one measured, for instance, in the test chamber (for gas temperatures of $t_g = 890^{\circ}\text{C}$, for the selected special profiles), blade temperatures of $t_s = 390^{\circ}\text{C}$ which, for $t_g = 1000^{\circ}\text{C}$, increased to 440° to 460°C .

Figure 1* shows the blade temperature as a function of the gas temperature for about 40 percent exhaust loading. The bottom line of the three lines corresponds to measured temperatures when the velocity head corresponding to a flight velocity of 500 kilometers per hour is fully utilized, whereas the line above it corresponds to a cooling by air of an impact pressure of half the former magnitude. The values of the top line apply for the case that the energy of the cooling relative wind remains practically unutilized and the air rather flows toward the blades due to the ventilation effect of the selected profiles.

With the aid of drag measurements on blade cascades the measured blade temperature values could be precalculated with sufficient accuracy from the heat conduction and emission. Therewith an extension by calculation of the curves beyond 1000°C - the highest exhaust loading temperatures used so far - is made possible; it can be seen in the shaded range in figure 1.

In this manner it can be determined that, for a blade temperature of about 600° which is to be considered as permissible for modern materials, the gas temperature ahead of the nozzles may be increased, beyond the extent required according to the expositions below, to values of 1400 to 1600, without an unduly large decrease of the strength of the rotor-blade material or of the operating efficiency of the turbines.

Since thereby the entire temperature range to be considered is controllable, the gas turbine with or without combination with a jet propulsion plant as main engine becomes a technical possibility.

With mounting gas temperature, the following quantities increase:

- (1) The thermal efficiency in the temperature range under investigation,
- (2) The power concentration; that is, the following quantities decrease:
 - (a) Specific air consumption
 - (b) Space requirements of the engine
 - (c) Engine weight per unit power
 - (d) Specific fuel consumption because due to lower specific air consumption, the compressor inlet diameter can be decreased lowering the compressor inlet relative Mach number and allowing increased rpm and therefore compressor pressure ratio.

*NACA Editor's note: Many of the notations on the figures were practically illegible in the only available copy of the German version of this paper. The figures herein represent the best possible reproductions that could be obtained with the limitations thus imposed.

II. Power Plants Investigated

In the DVL a number of power plants were investigated by calculation, every one of which represents a further development of the previous one; they are designated in figure 2 as power plants A to D and A* to C*. A to D operate on the basis of the constant-pressure method, thus as through-flow engines with time-constant pressure, whereas A* to C* operate as pulse engines with successive work processes.

The power plant A represents a through-flow engine proper of the type mentioned repeatedly in foreign literature. The compression takes place exclusively by the impact pressure. After the air has entered the hollow interior, fuel is supplied, burned, and discharged rearward. The propulsion is due to the pulse difference between outflow and inflow of the working medium. Since the thermal efficiency is decisively influenced by the pressure ratio of the working medium, the true field of economical operating possibilities lies in the supersonic region. Since, however, supersonic flight is as yet to be considered an unsolved problem with respect to the airplane as well, the investigations were made with the principal aim of examining the possibilities of application in the subsonic region (for about 70 percent to 90 percent of sonic velocity, thus Mach number $M = 0.7$ to 0.9). Aside from their use as main power plants, such propulsive devices would also be of importance as a means of supplementing short-term high propeller output maxima for high-speed aircraft which may possess as their main power plants aggregates of the other designs to be discussed.

The increase of fuel economy in the range of very high flight velocities is the result of the small pressure ratios in the impact compression of small relative flow velocities. The power plant B therefore provides for an additional compression in the interior of the body the flow passes, which further compresses the air (precompressed by the relative-wind impact) in a centrifugal compressor driven by a gas turbine. This turbine is designed in such a manner that it only yields the torque required for the compression which can be done either by an increase of the back pressure of the turbine ahead of a successively arranged jet nozzle, or - if the pressure in the turbine blades should not be increased to a noteworthy extent beyond the external pressure - by full stress-relief in the turbine nozzles and enlargement of the blade angles (Part II) with the gas being discharged rearward with little diminished velocity and, by reaction effect, propulsion being produced. For practically attainable flight velocities better fuel-consumption figures than for power plant A may be attained, owing to this additional compression.

It is true that a larger compression ratio thermodynamically utilizes the fuel heat to an increasing extent, that is, high gas velocities are produced more economically; however, a satisfactory

conversion of the high gas velocities into thrust output remains, for jet propulsion proper, still dependent on very high flight velocities. A further improvement in the direction of economical-propulsion production for practically attainable flight velocities consists in considerably lowering the high gas velocity in the turbine which can utilize it with better efficiency than jet propulsion, so that a turbine output much larger than that required for driving the compressor is obtained. Thus, there results the power plant C, where the largest part of the gas output is converted in the turbine which drives, aside from the compressor, a propeller over a gear, whereas the rest of the gas energy as discharge energy from the turbine, - as it were as low pressure or exhaust-jet device - produces propulsion by reaction effect.

It is the advantage of this arrangement that the consumption of the high gas velocities is, so to say, distributed between two power engines; each of them is able to utilize its allotted range with good effectiveness. The dependence of the fuel consumption on the flight velocity is considerably less pronounced for the power plant C than for the power plants A and B due to the fact that only a very small part of the total energy takes effect by reaction.

The power plant D, finally, shows an even slighter influence of the flight velocity; it, therefore, can be utilized with good economy even for very low flight velocities. Here - with allowance made of the heat-exchanger weight - a preheating of the compressed air by the hot exhaust gases is provided for; obviously this preheating represents (by restoring part of the exhaust heat into the process) thermodynamically an improvement of the method which is the greater, the higher the temperature to which the combustion air is preheated. Furthermore, a high preheating has favorable effects on quality and speed of the combustion, thus also on the size of the combustion chamber. Preheating is limited by the weight of the preheater.

The power plants A* to C*, investigated in tests parallel to the arrangements A to D, have the advantage of the better fuel utilization of the pulse method with precompression as compared to the constant-pressure method, and, in a given case, the advantage of the absence of any compressor; however, they have the disadvantages of a more complicated structure due to the requirement of shrouding organs at the hot combustion chamber. Suggestions for a solution exist, but practical experiences have yet to be gathered. The structural expenditure depends, above all, on the number of working cycles which can be attained per second. The improvement in fuel utilization is obviously greatest for the power plant A*, the consumption of which is even lower than that of the power plant B.

The properties of power plants of this type are of special interest with respect to the following three points:

- (a) Fuel consumption
- (b) Specific air consumption, that is, weight and space requirements
- (c) Engine weight per unit power

III. Fuel Consumption

The fuel consumption for a prescribed flight velocity decreases from A to D. The value β_{200} is plotted in table 1 from the curves of figure 3, the value β'_{200} (cf. below), from figure 4. The value β'_{200} characterizes the ratio between the fuel consumption of any special power plant and that of a modern Otto-cycle engine, referred to the thrust output at 200 meters per second flight velocity, and with consideration of the drag of the radiator.

A value of 6 kilometers was always selected as comparative altitude; on one hand at this height, the advantages of high-altitude flight with respect to flight velocities are already effective; on the other, one may there maintain, for a velocity head of about 0.15 ata at 200 meters per second, an automatic ventilation of the altitude chamber with a pressure and a temperature corresponding to about 4 kilometers altitude.

The fuel consumption depends on

- (1) The flight velocity
- (2) The gas temperature
- (3) The compression ratio

The influence of the flight velocity is shown in figure 3. It is caused, first, by the precompression by means of the relative-wind impact and second, by the utilization of the discharge energy by jet-reaction effect. The fuel-consumption values are compared to those of a modern Otto-cycle engine; it must, however, be taken into consideration that the comparison of the fuel-consumption figures must be referred to an airplane with equal service load and equal surface load.

The reduction of the main cross-sectional area, diminution and lighter construction of the wing unit, etc., make a comparison of the fuel-consumption figures, referred to the shaft or thrust output, appear inadequate. The turbine power plant must, therefore, be credited with

weight and drag of the radiator and with the reduction of the weight of the power plant due to smaller weight per unit power.

By replacing the Otto-cycle engine in a pursuit plane, where the power plant represents about 40 percent of the weight, by a C power plant of equal output the flight weight without fuel may, for instance, be decreased to about 70 percent. It is found that, in order to obtain the same velocity with an Otto-engine plant, considerably more power is required. In a comparison between spark-ignition engine and C power plant this power increase must be put down as power loss of the spark-ignition engine; it augments the consumption in horizontal flight of a spark-ignition engine compared to the C power plant. Hence there results in figure 3 the top line indicated for the Otto-cycle engine and in table 1 the comparative value β'_{200} . Since the fuel weight is not taken into consideration, this line is accurately valid only for C power plants with $\beta'_{200} = 1$. If this value exceeds 1, the comparative line for the Otto-engine approaches somewhat the line between the two-cross-hatched strips, the more it exceeds this value, the larger is the planned range of the airplane. For the short flight times of the pursuit plane, this influence is slight.

The combustion efficiency was assumed as 95 percent. The power plant C is plotted in figure 3 in two types: first, for a one-stage arrangement with a pressure ratio of about 2.7 and second, for a two-stage arrangement with a pressure ratio of about 3.9. The efficiencies of turbines and compressors were assumed in accordance with present knowledge concerning supercharger and exhaust turbine efficiencies.

From table 1 and figure 3 it follows that the power plants C and D promise ability of competing with the present Otto-cycle engine also with respect to economy. In contrast it can be seen that the power plants A and B attain only for very high flight velocities the specific fuel consumptions which make a certain flight duration possible.

If the comparison is based not on a pursuit airplane but on an airplane where the power plant weighs less than 40 percent of the total weight, the β'_{200} values lie between those indicated in table 1 and the β_{200} values given alongside. The calculation showed that a high-speed bomber with a speed of about 500 kilometers per hour, if a C power plant is used, can transport - up to a range of about 2600 kilometers - a larger service load than if propelled by an Otto-cycle engine.

In figure 4 the comparative fuel consumption values β'_{200} described above are plotted against the thrust output per kilograms of air per second. The diagram shows in what manner the fuel consumption decreases with increasing output per kilogram specific air consumption,

thus power concentration is increased, with simultaneous increase of the weight per unit power. For comparison, the values of the Otto-cycle engine also have been plotted for which power concentration and weight per unit power are comparatively very high while the fuel consumption referred to the thrust output agrees as to order of magnitudes with the most favorable data for the special power plants.

If one considers the influence of the gas temperature on the fuel consumption, an even stronger decrease of the fuel consumption with increasing temperature is shown for the power plant D (with preheater) than for the power plant C.

The reason is that the waste heat of the gas, mounting with increasing initial temperature, is again supplied to the process by the preheater. The amount of the temperature is limited by the material of the turbine and also by the weight of the preheater. For reaction power plants proper the most favorable temperatures lie, due to the decreasing jet efficiencies, lower than for the power plants C and D.

In figures 5 and 6, for the pressure ratios 4 and 6, fuel-consumption figures (D power plants) are plotted against the gas temperature for different constant terminal preheating temperatures of the air, for two different pairs of efficiencies. It is shown that the optimum fresh-gas temperature increases with decreases in preheating and efficiency.

Furthermore, the fuel consumption is influenced to a great extent by the compression ratio. Here it is of importance that the latter can be increased beyond the amount corresponding to the adiabatic work head of the compressor by utilization of the relative-wind impact. Figure 7 shows for C power plants the fuel consumption as a function of the compression ratio, for various efficiencies of the expansion and compression. The fuel-consumption values in grams per thrust horsepower are plotted against the pressure ratios which are obtained including utilization of the relative-wind impact pressure. The pressure ratios considered lie between 3 and about 5.

IV. Specific Air Consumption

The power concentration, that is, the thrust output of the power plant per kilogram gas, increases from A to D. Moreover, the energy of the gas increases in proportion to the increasing fresh-gas temperature so that the required specific air consumption decreases correspondingly. The influence of the flight velocity on the specific output (per kg gas) is treated in more detail in Knörnschild's "Einzelheiten über Frischgas-turbinen und Rückstossertriebwerke" (Details about fresh-gas turbines and reaction power plants).

The dependence of the power concentration on the compression ratio can be seen from figure 8, where the useful power per 1 kilogram specific air consumption is plotted against the pressure ratio. It is demonstrated that with mounting efficiencies and temperatures the most favorable pressure ratios also increase. In the range in question the optimum values of the combustion pressure are comparatively low.

V. Weight per Unit Power and Its Influence on the Specific Fuel Consumption

Of special importance for the evaluation of such power plants is the weight per unit power which was roughly calculated for a number of such models according to preliminary results. Power-weight ratios of power plants ready for service were compared, referred to the thrust output, including (as far as present for the respective case) propeller, cooling radiator, coolant, engine suspension, etc.

It is readily apparent that, as table 1 shows, the roughly precalculated weight per unit power of the power plants, referred to the thrust output, increases from A to D in proportion to that of the spark-ignition engine. The value γ indicates the ratio between the weight per unit power of any power plant and that of an installation with water-cooled Otto-engine. Therein results for today's Otto-engine a power-weight ratio of 1.2 to 1.4, for a C power plant of 0.4 to 0.5, and for a D power plant (with preheater) of 0.5 to 0.65. This would signify that the weight of the power plant decreases by transition from the reciprocating engine to a C power plant to about 35 percent, to a D power plant to about 45 percent. For air-cooled engines the weight per unit power of the reciprocating engine would have to be assumed smaller by about 10 percent, thus the values given should be multiplied by 1.1.

As is well known, the advantages of small weights per unit power are:

- (1) More favorable conditions with respect to maximum velocity obtainable
- (2) Large increase of the rate of climb. The calculation resulted, for instance, for power plant C in a rate of climb 1.3 to 1.6 times as high, and for optimum conditions (empty tanks, etc.) in more than double the rate of climb of an Otto-engine.

- (3) Increased permissible load up to a critical range where increased fuel consumption and reduced weight of the power plant cancel each other.
- (4) Certain improvements with respect to take-off quality and flight ceiling.

The effect of these advantages is the stronger, the greater the portion of the flying weight which the power plant represents.

VI. Installation Examples and Concluding Remarks

It must be mentioned with respect to the fundamental structure of such thrust producers that the power-plant arrangements B and C may be combined in various ways, for instance, by subdividing the through-flow into a high-compressed part (for production of the power-engine output) and a low-compressed part (for thrust production by reaction). The precalculation yields fuel-consumption values which approach, without use of a propeller proper, those of a C-power plant.

In figure 9 a few installation possibilities for power plant C are compiled. Conditions are always more favorable when the propeller is arranged behind the power plant as pusher propeller. Arrangement 1 has the advantage of a very good impact ram compression of the outer air, arrangement 2, that of a particularly good cooling of the turbine rotor which in the wing-nose is openly exposed to the relative wind. The combustion chambers lie laterally in front of the rotor and could well be disposed in the wings. The arrangements with puller propellers result in somewhat less favorable conditions for the impact ram compression of the outer air. Arrangement 3 has the advantage of a concentric and balanced gear arrangement; arrangement 4 will perhaps show somewhat less gear losses due to a small number of points of support, on the other hand the tooth system is not balanced. Arrangement 4 takes in the outer air in a closed jet with less losses, but the gear design appears less favorable.

For large thrust outputs more favorable conditions of installation frequently result by distribution between several turbines. Aside from a simple parallel connection of several aggregates which may eventually operate on one gear, a division into turbines for compressor propulsion and turbines for propeller propulsion may be considered. This division has the advantage that different rpm may be selected for the separate turbines, according to their different purposes, thus enabling savings in weight and space.

The values of the Otto-engine mentioned in the report correspond to normal values at present attainable in operation. With the possibilities

of improvement taken into consideration, to which points the further development of the motor techniques (exhaust gas turbines, fuel injection, jet exhaust stack reaction, etc.), the consumption ratio between Otto-engine and special power plant may shift somewhat in favor of the Otto-engine.

For the evaluation of the development of power plants of the suggested type the fact is important that (at least in the power plants operating according to the constant-pressure method) in almost all parts known engine elements are used under operating conditions which do not decisively differ from previously tested ones, except perhaps in output.

TABLE 1

Power plant	Method	Propulsion by	Power/weight ratio (a)	γ (b)	β_{200} (c)	β'_{200} (d)
A	Constant pressure	Jet	0.05-0.15	0.08	3.95	3.1
B	Constant pressure	Jet	0.15-0.25	0.15	2.1	1.7
C	Constant pressure	Propeller and jet	0.35-0.55	0.35	1.4	1.15
D	Constant pressure	Propeller and jet	0.50-0.65	0.45	1.10	0.95
A*	Explosion	Jet	0.1-0.25	0.15	1.8	1.5
B*	Explosion	Jet	0.2-0.45	0.25	----	----
C*	Explosion	Propeller and jet	0.3-0.55	0.35	1.3	1.15
C* _{ZV}	Explosion	Propeller and jet	0.4-0.60	0.40	1.25	1.10
Otto-motor			1.2-1.4	1.0	1.0	1.0

^a Power-weight ratios apply to the engine ready for service including radiator, suspension, cowling, and propeller, referred to the propulsion (propeller efficiency = 75 percent).

^b γ = ratio between the power-weight ratios of power plant and Otto-engine.

^c $\beta_{200} = \frac{b_{\text{power plant}}}{b_{\text{Otto engine}}} = \text{comparative value for the fuel consumptions with consideration of the radiator influence on the consumption for 200 meters per second flight velocity and 6 kilometers flight altitude.}$

^d $\beta'_{200} = \frac{b_{\text{power plant}}}{b_{\text{Otto engine}}}$ with consideration of the radiator influence and the weight influence for equal surface loading on the consumption (for pursuit planes) for 200 meters per second flight velocity and 6 kilometers flight altitude.

PART II. DETAILS ON THE COMPARISON OF SPECIAL POWER PLANTS

By E. Knörrschild

Abstract:

The exhaust turbine and jet propulsion systems operating by constant pressure as well as by the pulse method, which were mentioned in the first part of this report, are treated in more detail. In particular, the influence of the ram pressure, gas temperature, preheating of the fuel, and of the pressure ratio on the thermal efficiency and the power concentration are discussed. The regulation of such power plants is briefly treated. In an appendix a generally valid equation is given for the variation of fuel consumptions with the variation of combustion temperature, of compressor and turbine efficiencies, and of preheating.

Outline:

- I. Fuel Consumptions and Specific Outputs
- II. Various viewpoints Regarding the Design of the Power Plants A to D
- III. Power Plants Incorporating the Pulse Method
- IV. Regulation
- V. Appendix, Variation of the Fuel Consumptions

The following discussion refers to the power plants enumerated in the first part of the present report which operate partly according to the constant-pressure, partly according to the pulse method.

The investigations were to give, on one hand, more details on the problem of how the thermal efficiency or the specific fuel consumption of such power plants may be influenced, respectively, by utilization of the ram pressure, by suitable selection of gas temperatures, preheating, and pressure ratio of the compression; on the other hand, they were to show what effect these influences have on the power concentration, thus on the thrust output obtainable from 1 kilogram of air. A high power concentration (which decisively influences the power-weight ratio and the space requirement) is just as much a preliminary condition for such a power plant to be able to compete with the Otto-motor as is a low fuel consumption.

I. Fuel Consumptions and Specific Outputs

Figure 3 shows, dependent on the flight velocity, the variation of the fuel consumption figures, referred to the thrust output, whereas figure 10 shows the variation of the specific outputs, that is, of the output per kilogram of air per second or, respectively, of the potential (kinetic) energy of 1 kilogram of air.

Almost throughout, the consumptions decrease with increasing flight velocity since the thermal efficiencies rise owing to the increase in pressure ratio due to the ram pressure. For equal heat supply, that is, for equal combustion temperature and preheating, the specific fuel consumption is inversely proportional to the specific output. Thus an increasing power concentration corresponds to a decreasing consumption.

It can be seen that, if the energy conversion is divided between propeller and jet thrust, for small flight velocities an increase in outputs occurs with increasing contribution of the propeller. An invariable value was substituted as propeller efficiency; for small flight velocities it lies at the lower limit of the attainable range; for higher flight velocities taken into consideration in the comparison, it can probably just be reached when special measures are applied.

In detail, the following results may be seen, for instance, from the comparison of figures 3 and 10.

Since for the power plant A the compression is given exclusively by the ram pressure, there result, for the flight velocities of 500 to 700 kilometers per hour attainable at present, relatively high consumptions of 3.0 to 1.5 kilograms per horsepower-hour, referred to the thrust. The very small specific outputs require considerable through-flow quantities (20 to 30 kg air) which can, however, be controlled in view of the simple construction.

Concerning power plant B, figures 3 and 10 show that an increase of the compression ratio beyond the amount possible in case of pure ram pressure by additional compression lowers the consumption as much as to 800 to 1000 grams per horsepower-hour, whereas the specific outputs have increased so that for a 1000 horsepower power plant, for one-stage additional compression, air quantities in the order of magnitude of 10 to 20 kilograms per second are sufficient. Furthermore, the additional compression enables the power plant B to produce static thrust; this is not possible for power plant A due to the lack of ram pressure.

Power plants C and D show so great an improvement of conditions in the velocity range mentioned that here the order of magnitude of the fuel consumption of Otto motors is already reached, if one refers the

consumptions¹ to the thrust output required for equal service load. In the case of power plant C the output maintains, due to additional jet thrust effect, a tendency to increase with the flight velocity whereas in the case of power plant D the greatest part of the discharge energy is absorbed by friction at the passage of the gas through the preheater and thus is lost for the thrust. For power plant D the influence of the flight velocity is, therefore, limited to an increase in dynamic pressure (thus in the pressure ratio) and in air input energy; the lower power is particularly noticeable at high flight velocities, because of elimination of the jet-reaction effect.

Figure 11 represents the connection between the fuel consumptions and the specific outputs for the various special power plants. Beginning with power plant A, which has high consumption and low specific output, the consumption decreases while simultaneously the specific outputs attainable increase. The more favorable values (in the diagram at right) are obtainable only at the price of structural complications or, respectively, increased weight per unit power. Thus power plant A which shows the lowest specific output has the lowest weight per unit power. In contrast, the spark-ignition engine combines with its high specific output of about 900 horsepower per kilogram of air per second, referred to the thrust, by far the highest weight per unit power since it requires, as a reciprocating engine, (due to the complication of the crank mechanism) a high construction expenditure for utilization of its very small rate of air flow.

The same figure also classifies the power plants operating according to the pulse method (denoted by *) which are treated in more detail below. Power plant A* shows considerably more favorable values than A and even lower fuel consumptions than power plant B. The power plants C* and C*_{zv} are very favorable and attain the range of the spark-ignition engine with respect to fuel consumption. The weight per unit power of these power plants depends to a great extent on the obtainable number of working cycles per second, but is probably higher than that of the corresponding constant-pressure power plants.

The ranges of the separate power plants which may be seen from diagram 11 follow - with respect to order of magnitude - closely a hyperbolic curve that satisfies the equation $B = bN = \text{const.}$; that is, the absolute fuel consumption per kilogram of air B as product of the specific consumption b and the specific output N remains constant when the gas temperature (and the preheating) does not vary. The gas temperature to which the absolute consumption B is approximately proportional appears as parameter.

¹cf the first part of this report, p. 6.

A comparison of the fuel consumptions of such a power plant of 1000 horsepower with those of a 1000 horsepower Otto motor may be performed about as follows: Assume that the comparative motor is designed for 6 kilometers critical altitude like the power plants C and D. Its consumption, referred to the shaft output on the ground, is 215 grams per horsepower-hour and, by taking into consideration compressor output and gear loss at 6 kilometers altitude, 250 grams per horsepower-hour; referred to the thrust output at 6 kilometers, about 330 grams per horsepower-hour. With radiator drag including interference effect (which for 200 meters per second flight velocity reaches 8 to 12 percent) taken into account, this consumption increases to about 360 to 380 grams per horsepower-hour. The radiator drag must be taken into consideration since the special power plants investigated may be designed without radiator.

Beyond this, the influence of the reduced weight makes itself felt - under the presupposition of equal surface loading² - insofar that for a pursuit plane with a flight velocity of 200 meters per second the consumptions of the Otto motor have to be assumed with 435 to 465 grams per horsepower-hour as compared to 510 to 550 grams per horsepower-hour for the power plant C.

Unpublished investigations of the DVL³ have proved that, if a C power plant is used as propulsion aggregate, the limit to which the maximum speed of an airplane provided with an Otto motor is subject, even for utmost increase of the motor output, may be extended by a considerable amount.

In a comparison between power plant D and an Otto motor the result would be a fuel consumption of the Otto motor of 400 to 430 grams per horsepower-hour as compared to 380 to 420 grams per horsepower-hour for the D power plant, thus approximately conformable amounts. This superiority is maintained with respect to order of magnitude for the D power plant due to the slight dependence of the specific consumption on the flight velocity up to velocities of 360 kilometers per hour.

If a reduction of the wing area (as made possible by the saving in weight for a special power plant compared to an Otto motor) is to be excluded, there exists the possibility of increasing the additional loading while keeping the wing area constant. In the latter case it is shown (cf. fig. 12) that below the maximum range - which here amounts to about 2600 kilometers for both cases - a high-speed bomber with 500 kilometers speed and with a C power plant can transport larger service loads than one provided with an Otto motor.

²The flight mechanical considerations are based on Göthert's findings "Einfluss von Veränderungen des Fluggewichts...auf die Flugleistungen" (Influence of changes in flying weight...on the flying performances), Untersuchungen und Mitteilungen Nr. 426.

³performed by Matt, DVL

II. Various Viewpoints Regarding the Design of the Power Plants A to D

In detail, the following viewpoints must be mentioned concerning the power plants A to D:

Noteworthy advantages of the power plant A are⁴: its great simplicity, its low structural weight (if one succeeds in keeping the combustion chamber sufficiently short by decreasing the combustion periods), furthermore its superiority as thrust producer at higher speeds than can be obtained with propeller power plants, and, finally, the basic suitability of one and the same power plant for flight at arbitrary altitudes.

Disadvantages of this power plant are: the impossibility of producing static thrust, the high fuel consumptions for flight velocities v attainable at present, and the comparatively low power concentration. Owing to the relatively small flow velocities, large cross-sectional areas and correspondingly high intrinsic drags are produced.

Although the power plant is, characteristically, suitable chiefly for speeds far beyond sonic velocity, the discussion will be restricted (because of limitations regarding the airplane) to airspeeds attainable with existing airplanes.

Figure 13 shows how fuel consumption and thrust output attainable per 1 meter² cross-sectional area vary as functions of the combustion temperature t_g and the maximum velocity w_1 of the through-flow through the combustion chamber. The diagram applies to flight velocities corresponding to $M = 0.8$ and for 11 kilometers flight altitude. With modifications of the flight altitude the thrust output varies approximately in the proportion of the specific weights of air. The diagram also makes an estimate of the additional consumption due to the intrinsic drag possible insofar as the intrinsic drag is given with the cross-sectional area and the length of the combustion chamber resulting from w_1 with the aid of combustion period control. The intrinsic drag amounts, for instance, for 6 kilometers flight altitude, 800 kilometers per hour flight velocity, distribution of 1300 horsepower between two power plants and combustion to 600° C, to about 1.2 percent of the produced thrust.

For a prescribed flight velocity, the thrust may be modified, in order to initiate various states of flight, by injection of more or less fuel, with different values assigned for combustion temperature as well as for discharge velocity. Since the variation in temperature

⁴The following expositions concerning the power plant A are taken from an investigation being carried out by V. Speiser.

surpasses the one in discharge velocity, a reduction of the consumed air quantity is linked with an increase in discharge velocity, if the outlet cross section is constant. Hence follows the rule, important for the design, of letting the compression take place to the greatest part unguided (that is, without a diffuser) since the airstream then automatically maintains the necessary expansion whereas, if the flow is guided through a diffuser, inlet and outlet cross section of the power plant agree only for a standard condition.

The use of the power plant treated above offers flight mechanical advantages. They lie in the fact that, due to the greatly variable rate of air flow and output, respectively, on principle the flight is possible at the most favorable gliding angle for arbitrary speed if the corresponding flight altitude is maintained. This is, therefore, also valid for particularly high speeds, of chief importance in view of the fuel consumption. Unfortunately, the aerodynamic characteristics of wing profiles in use at present considerably deteriorate from flight velocities corresponding to about $M = 0.6$ onward; this causes deterioration of the optimum attainable gliding angles so that, in the velocity range showing the best fuel consumption values regarding the power plant, aerodynamic influences endanger the economy. A corresponding extension of the boundaries sketched here is to be expected by development of profiles and airplane forms suitable for such speeds.

According to a special investigation regarding the airframe⁵, flight durations of about 50 minutes, (of about $1\frac{1}{2}$ hours under particularly favorable assumptions) can be attained for 800 kilometers per hour. Flight duration was found to be practically independent of airplane size. The power plant seems to offer favorable prospects as additional aggregate, when it is applied for instance to pursuit airplanes with Otto motor for temporary extra power. The maximum speed of pursuit airplanes may be increased, by arrangement of such a power plant, for instance from about 585 kilometers per hour to about 800 kilometers per hour, if - for 1.5 hour total flight duration - 15 minute operating periods are required for the additional aggregate. The price of this advantage is a loss of speed if the aggregate is not used, which probably amounts to about 10 to 15 percent in comparison to the airplane without additional aggregate.

The power plant A has been treated in a number of foreign publications. Besides theoretical and flight technical considerations one may find, for instance, data concerning a French project earmarked for construction which promises, for flight velocities of 900 to 1000 kilometers per hour, outputs of 10,000 to 20,000 horsepower and a range of 4000 kilometers. Compared with the results of the investigations performed at the DVL these data must be called very optimistic if not downright impossible.

⁵Carried out by Göthert and Matt, DVL.

For the power plant B a distribution of the energy between turbine and jet nozzle must be provided for in such a manner that the turbine takes merely the compressor power out of the gas energy. An investigation showed that an increase of the turbine back pressure beyond the external pressure for the purpose of distributing the pressure energy between turbine and jet nozzle does not result in a noteworthy improvement in economy; on the contrary, the total energy can be used up to that of the back pressure; blade and nozzle angles must be chosen so that the turbine takes from the expanded jet merely the power required for the compression whereas the rest, as discharge energy, is used for thrust. Since the discharge energy is not to be valued as a loss, the conception of rotational efficiency loses its significance for turbines of this type. Velocity triangles as shown in figure 14 are produced, which are different from the customary ones. As can be seen, the rotational components for supply of the compressor power are small in comparison with the axial components. The blade exit angle lies so that the gas leaves the wheel as nearly as possible in the axial direction. The slight deflection in the nozzle as well as in the rotor blade leads one to expect very small flow losses. Due to the high axial components, the absorption capacity of the turbine wheel is considerably increased compared with a standard design, that is, small blade lengths result even for large gas quantities.

In the case of the C power plant the total thrust output is made up of the propeller output N_{prop} and the jet output N_{jet} . The optimum distribution of the total expansion energy between turbine and jet may be determined by calculation. The results are represented in figure 15. As the diagram shows, the maximum output is produced by apportioning approximately 75 percent of the energy to the turbine while the rest is converted into jet thrust. This distribution, most favorable for the total thrust, happens to be the same which results for standard constant-pressure turbines with customary discharge loss. The position of the maximum is a function of the air propeller efficiency, here assumed with 75 percent. A deterioration of this efficiency shifts the maximum in the direction toward a larger share of the jet thrust. A reduction in flight velocity has the opposite effect.

The influence of the fresh-gas temperature on the fuel consumption of the C and D power plants is represented in figure 16. The dependence on the temperature is insignificant for the C power plant within the temperature range of the figure. The optimum consumption lies, for the chosen assumptions, at about 1300° C. For the D power plant the consumption decreases with rising gas temperature, under the assumption of approximately constant preheater areas. A limit for preheating is set by the heat resistance of the heat-exchanger metal sheets and by the weight of the preheater. The influence of the preheating temperature on the consumption is considerable; likewise, however, the influence on the weight. Reasonable conditions result for preheating temperatures of about 550° to 650° C, if gas temperatures of 1200° to 1300° C can be

allowed. From about 650°C onward, a further improvement in thermal efficiency is obtainable only at the price of very considerable increases in weight. At very high speeds the air-absorbing energy for the D power plant becomes noticeable in a reduction of the output, since no equivalent reaction energy is at disposal.

A more favorable yield in output may be obtained by putting a small pressure energy compared to the surroundings at the disposal of the gas at its discharge from the preheater. Thereby the reaction effect of the discharged gas is increased more strongly than the turbine output is reduced due to the corresponding reduction in turbine heat energy. Figure 17 shows, for a certain case, the calculation of the variation of the specific consumptions as a function of the ratio of pressure at the preheater outlet to pressure of the surroundings. One recognizes that the greatest part of the possible reduction in consumption may be obtained even for very small pressure ratios (1.05 to 1.1).

Whereas for the C power plant optimum consumptions of about 510 to 550 grams, referred to the thrust, result, consumptions of 380 to 420 grams may be attained for the D power plant - it is true, only at the price of an increase in weight per unit power to about 1.3 to 1.4 times that of the C power plant. The dependence on altitude of thrust output and fuel consumption of a C power plant at 200 meters per second flight velocity is represented in figure 18. The variation in output and fuel consumption is here plotted against the flight altitude; output and consumption at 6 kilometers altitude were used as a basis of comparison. The figure shows how, with decreasing altitude, the thrust output increases due to the variation in air density. On the ground an output about 1.5 times that at 6 kilometers altitude is obtainable. The specific consumption slightly rises with decreasing altitude. The cause of this increase lies in the reduction of the pressure ratio appearing with increasing compressor inlet temperature for equal (adiabatic) work head of the compressor, and hence in the reduction of the thermal efficiency.

III. Power Plants Incorporating the Pulse Method

In contrast to the constant pressure method where the necessary compression ratio is produced in a compressor and the combustion takes place continuously in a combustion chamber open on both sides, in case of application of the pulse method the fuel-air mixture enters a closed combustion chamber where it burns while the pressure rises. Power plants of this type have the basic advantage of being able to dispense with a compressor. A precompression by the ram pressure is advisable in most cases. For prescribed initial expansion temperature a further compression by an axial or radial compressor driven by a turbine is recommendable only in case of very good utilization of the expansion energy.

A comparison between constant-pressure and pulse method is represented in figure 19. The thermal efficiency of the constant-pressure method is chiefly a function of the compression ratio which must be produced by the charge. By means of the pulse method reasonable fuel consumptions may be obtained without additional compression. The diagram shows the variation in output of the two methods, if the same gas temperature before the expansion is assumed as prescribed for both. Assume that the compression work (with an adiabatic compression efficiency of 70 percent) is delivered in every case by the expansion energy. The energy still at disposal after subtraction of the compressor output may be converted into thrust in a turbine or in jet nozzles. For the constant-pressure method an efficiency of this conversion of 70 percent was assumed, as can be obtained in case of application of turbines with utilization of the discharge energy in a jet nozzle. With the pulse method, on the other hand, only about 33 percent is obtainable for pure jet thrust, and about 40 to 50 percent in case of application of turbines which can utilize the high exit velocities at the start of the pulsating process with good efficiency. One recognizes from the diagram that for this efficiency a precompression does not yield any gain - under the presupposition that the combustion temperature cannot be increased.

For utilization of the ram pressure, figure 19 shows for both constant-pressure and pulse method a not inconsiderable increase in output due to the compression process being almost without loss.

Outputs and fuel consumptions for pulse power plants, as functions of the gas temperature in the combustion chamber, are represented in figure 20. The outputs increase considerably with rising gas temperature, due to the approximately proportional variation of temperature and pressure in case of constant-volume combustion, and due to the expansion energy which therewith greatly increases. The difference in yield of output for pure jet thrust and for use of a turbine wheel is considerable. For the probable obtainable efficiencies, additional compression does not produce any significant increase in output.

The fuel consumptions show optimum value at about 1000° C. For pure jet thrust they lie at approximately 700 grams per horsepower hour, referred to the thrust; for turbine operation, at approximately 500 grams per horsepower hour. An additional compression yields only an unimportant improvement in consumption.

IV. Regulation

The output of a fresh-gas turbine power plant is decisively determined by the heat energy and the gas flow quantity. The heat energy, in turn, is a function of the pressure ratio and the gas temperature. The regulation of such power plants, that is, for instance the transition

from full load to partial load, can thus be performed by variation of the three operating factors: gas flow quantity, pressure ratio, and gas temperature. A fourth possibility consists in destroying part of the produced output.

Thus the following types of regulation result:

- (1) The quantity regulation, that is, the regulation of the gas flow by variation of the nozzle cross sections of the turbine
- (2) The energy regulation:
 - (a) Influencing the pressure ratio by variation of the rpm of the aggregate (for instance by variable pitch propeller)
 - (b) Influencing the gas temperature by variation of the fuel supply
- (3) Destroying part of the output, that is, throttling ahead of the compressor (ahead of the combustion chamber) or ahead of the turbine.

Since, with a constant-pitch propeller, due to the variation in output which results by the influencing of the nozzle cross section, the gas temperature, or by the throttling of the charge air, the rpm automatically also changes, a variable-pitch propeller must be provided if, for constant rpm, one of the regulation factors 1, 2b, or 3 is desired to be variable.

Of the four types of regulation, the nozzle cut-off regulation influences the thermodynamic conditions of the power plant the least. Here merely the charge air quantity is reduced. The fuel consumption is influenced only by variation of the losses in loading, etc. This type of regulation requires the possibility of synchronizing and cutting-off nozzle segments which involves complications in construction.

In the case of temperature regulation which surely is to be regarded as the simplest type of regulation the fuel supply is varied. With the variation in combustion temperature the energy of the turbine varies, and therewith the specific output. With decreasing temperature the thermal efficiency usually deteriorates, that is, the fuel consumption increases slightly.

The regulation by throttling where the air pressure is throttled in the inlet or outlet cross section of the compressor must be considered the most uneconomical regulation. In spite of approximately equal (adiabatic) work head of the compressor, the turbine energy, and with

it the yield in output, is reduced. By the throttling - which represents destroying part of the output - the thermal efficiency is affected very unfavorably.

By only rpm regulation, the (adiabatic) work head of the compressor, and therewith of the turbine, may be varied. The thermal efficiency deteriorates with decreasing rpm because of the smaller pressure ratio at which the process operates, that is, the specific fuel consumption for partial load increases.

Investigations showed a combination of nozzle cut-off and temperature regulation to be the most favorable type of regulation where the larger regulating intervals are corrected by the synchronization and cutting-off of cross sections, and the smaller ones by temperature regulation.

APPENDIX

Variation of the fuel consumptions

For comparative calculation it is of importance to know the presumable course of fuel consumption in case of variations in combustion temperature, in compressor and turbine efficiencies, in temperature ahead of the compressor, and in preheating.

Following, an equation is derived which offers a simple synopsis of the conditions to be expected. Assume that it is based on the following data as comparative process: Compression with prescribed efficiency η_1 , heat supply with constant pressure, expansion with prescribed efficiency η_3 (cf. fig. 21).

The following symbols will be used:

b	specific fuel consumption
AL	useful work output
Q	$c_p(T_3 - T_2)$ heat quantity supplied
η_{th}	thermal efficiency
η_1	efficiency of compression (referred to isentropic curve)

η_3	efficiency of expansion
H_1	isentropic compression work per kg air
H_3	isentropic expansion energy per kg gas
T_1	initial temperature of compression
T_2	terminal temperature of compression
T_3	initial temperature of expansion
T_4	terminal temperature of expansion
ϵ	compression ratio
κ	ratio of specific heats
R	gas constant

Therewith is obtained:

$$b = \frac{63.2}{\eta_{th}} = \frac{62.2Q}{AL} \text{ g/hp-h}$$

$$AL = A \left[H_3 \eta_3 - H_1 / \eta_1 \right] = \left[(H/T)_3 T_3 \eta_3 - (H/T)_1 T_1 / \eta_1 \right] A$$

$$Q_{23} = c_{p23} (T_3 - T_2)$$

$$T_2 = T_1 + \frac{H_1}{\eta_1 427 c_p} = T_1 \left(1 + (H/T)_1 \frac{1}{427 c_p \eta_1} \right)$$

since $\frac{c_p}{A} = \frac{R}{1 - \frac{1}{\kappa}}$, there becomes

$$b = \frac{63.2R \left[T_3 - T_1 \left(1 + \frac{(H/T)_1}{R\eta_1} \frac{1 - \frac{1}{\kappa_{12}}}{1} \right) \right]}{\left(1 - \frac{1}{\kappa_{13}} \right) \left[(H/T)_3 T_3 \eta_3 - (H/T)_1 T_1 / \eta_1 \right]}$$

$$b = \frac{63.2R}{\left(1 - \frac{1}{\kappa_{23}} \right) (H/T)_3 \eta_3} \left[\frac{T_3/T_1 - \left(1 + \frac{(H/T)_1}{R\eta_1} \frac{1 - \frac{1}{\kappa_{12}}}{1} \right)}{T_3/T_1 - \frac{(H/T)_1}{(H/T)_3} \frac{1}{\eta_1 \eta_3}} \right] \text{ g/hp-h}$$

The equation shows that the fuel consumption depends on the pressure ratio which is implicitly contained in the value H/T , on the ratio between the maximum and the occurring minimum temperature of the working process, on the efficiencies for compression and expansion, and on the specific heats, the influence of which makes itself felt mainly in the value of κ .

The influence of the gas temperature on the consumption is clearly noticeable if the remaining variables, that is, H/T , η_1 , and η_3 , are made constant. The expression in parentheses in the equation above is, if no preheating is provided for, larger than unity and tends therefore with increasing gas temperature T_3 toward the value 1. This signifies that the surplus output of the expansion energy increases compared to the compression energy while the specific consumption decreases (cf. fig. 22). This reduction in consumption is counteracted solely, and only to a slight extent, by the influence of specific heat and dissociation which, with rising temperature, increases consumption.

If one further assumes η_1 and η_3 to be variable, one recognizes that with deteriorating efficiencies the consumption-reducing influence of rising gas temperature takes effect up to higher gas temperatures and that, moreover, the steep increase of consumption for low gas

temperatures ($b \rightarrow \infty$) where the expansion energy hardly balances the compression energy, is shifted to ranges of higher gas temperatures. Creation of part of the compression energy by the ram pressure is equivalent to an improvement in compression efficiency, that is, the optimum fuel consumptions shift to the range of lower temperatures. Additional jet reaction outputs could be included by modification of the expansion efficiency.

The influence of increasing compression, expressed in the value H/T , takes effect in a general lowering of the consumption values. Moreover, the ranges of minimum consumption shift toward higher gas temperatures. It may, for instance, be seen from the diagram that, for a gas temperature of 1300°K and efficiencies of about 0.7, the consumptions for $\frac{p}{p} = 4.6$ and 8 are approximately equal.

In the above equation one also can clearly see the influence of preheating. The subtrahend in the numerator of the expression in parentheses is proportional to the preheating. The equation shows that, according to the amount of preheating, the fuel consumption values may take a course rising or falling with the temperature T_3 .

If a process free from losses is assumed for compression and expansion (that is, $\eta_1 = \eta_3 = 1.0$), and if, furthermore, the specific heats of compression, heat supply, and expansion are equated and assumed to be independent of the temperature, it can be proved that the subtrahend of the numerator as well as of the denominator becomes T_2/T_1 , that is, the expression in parentheses assumes the value 1.

Consequently the equation for the consumption is simplified and is transformed into the well known form for constant pressure processes:

$$\begin{aligned}
 b &= \frac{63.2 \times 427 c_p T_3}{H_3} \\
 &= \frac{63.2 T_3}{T_3 - T_4} \\
 &= \frac{63.2}{1 - (p/p)^{\frac{\kappa - 1}{\kappa}}}
 \end{aligned}$$

SYMBOLS

v	flight velocity (m/s)
H	flight altitude (km)
b	specific fuel consumption (kg/hp-hr)
w_1/v	ratio between velocity in the combustion chamber and flight velocity
T_L	air temperature (degrees K)
T_g	gas temperature, combustion temperature (degrees K)
VW 600°	preheating of the compressed air to 600° C
N	output (hp)
N_{jet}	jet output (hp)
η_l	adiabatic compressor efficiency
η_{comp}	compression efficiency
η_{exp}	expansion efficiency
η_{prop}	propeller efficiency
η_{comb}	combustion efficiency
M	Mach number
H_u	lower heating value of the fuel (WE/kg)
c_1	absolute inlet velocity into the rotor blade (m/s)
c_2	absolute exit velocity (m/s)
w_1	relative inlet velocity (m/s)

u rotational velocity of the turbine wheel (m/s)

Δw_u sum of the rotational components of the relative velocity
(m/s)

Translated by Mary L. Mahler
National Advisory Committee
for Aeronautics

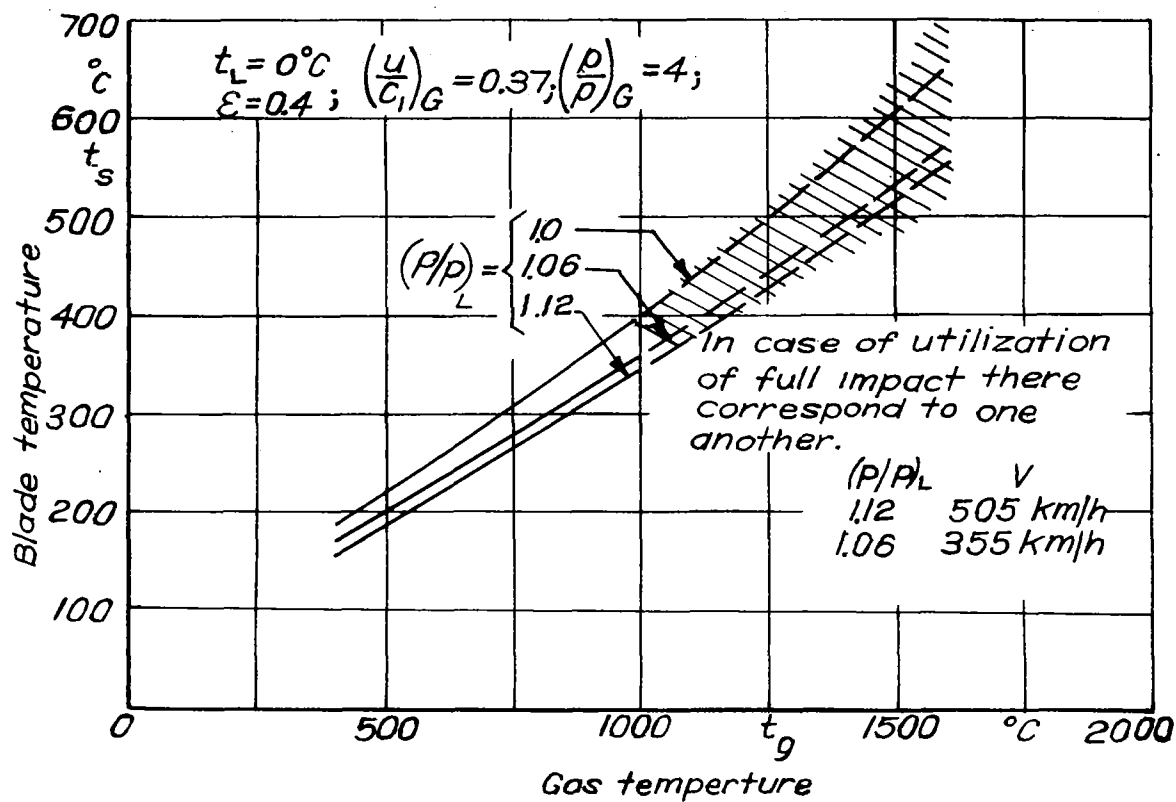


Figure 1.- Blade temperatures for gas turbines cooled by relative wind.

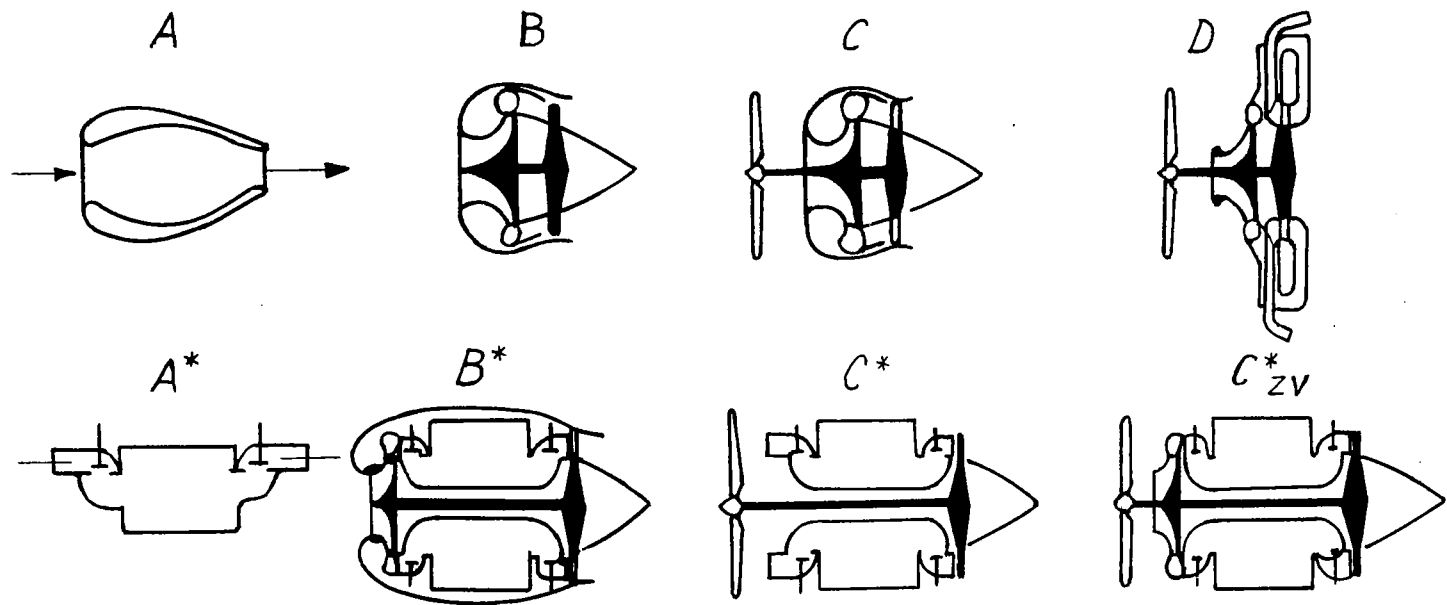


Figure 2.

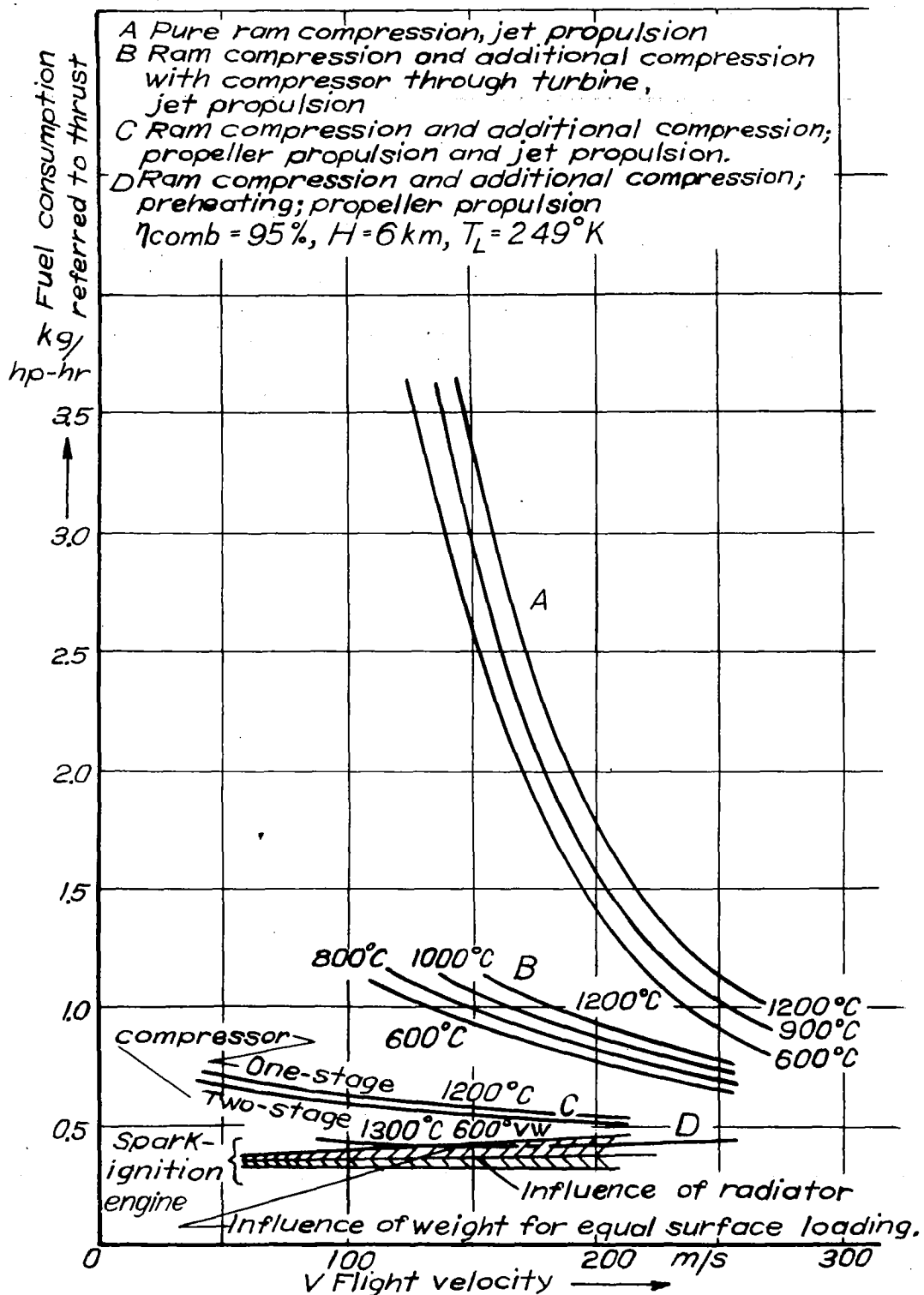


Figure 3.- Comparison of fuel consumptions for constant-pressure method.

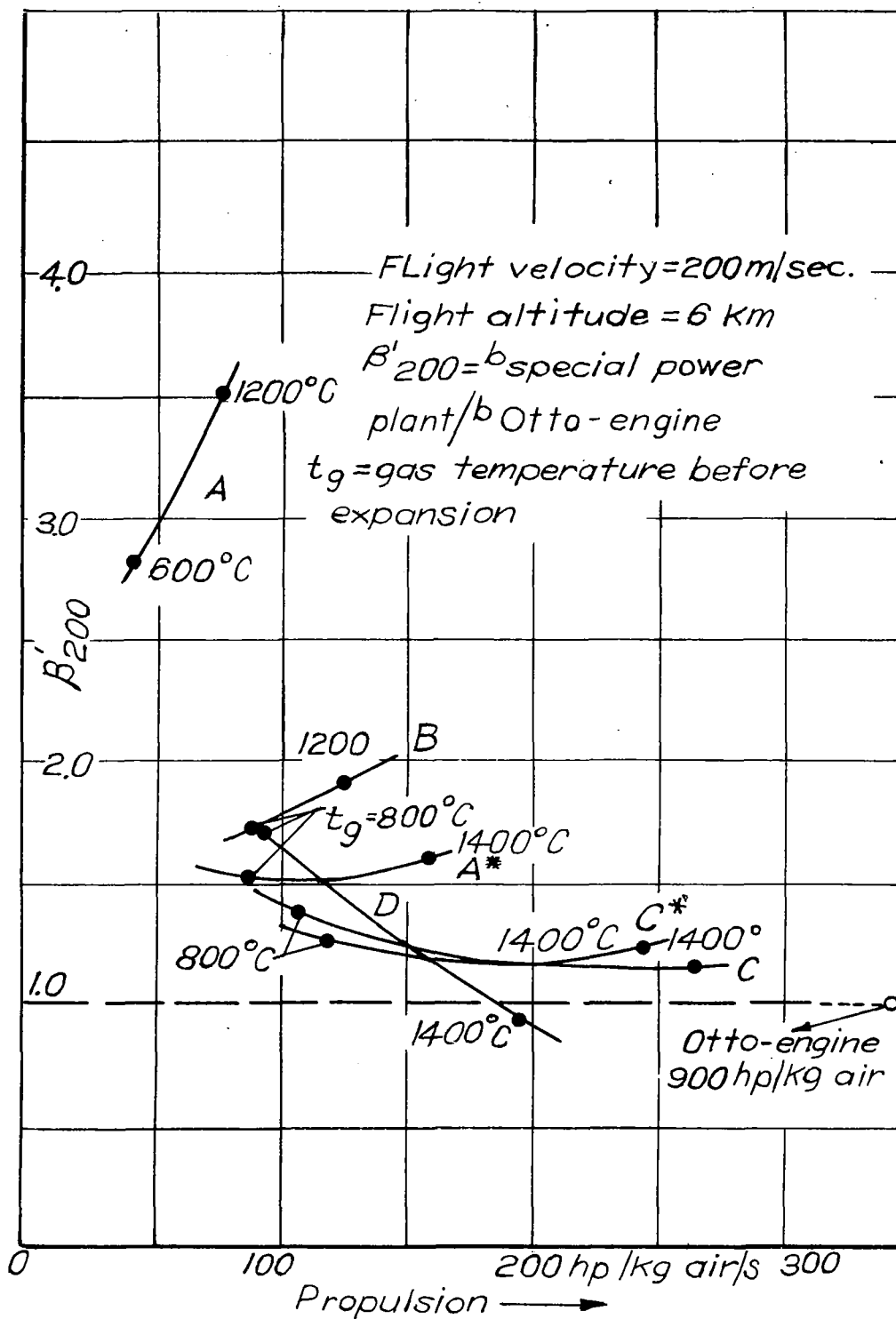
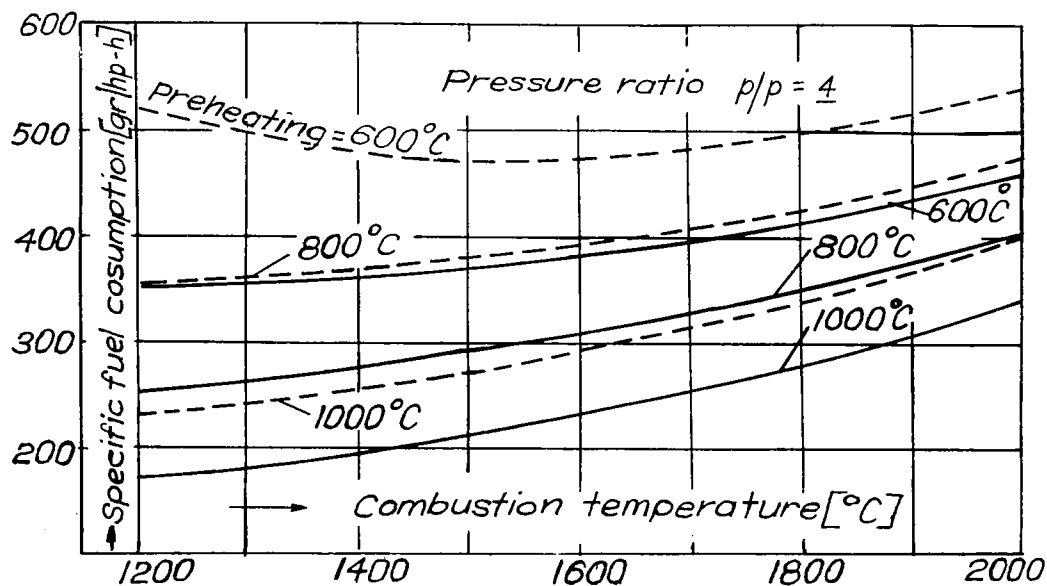
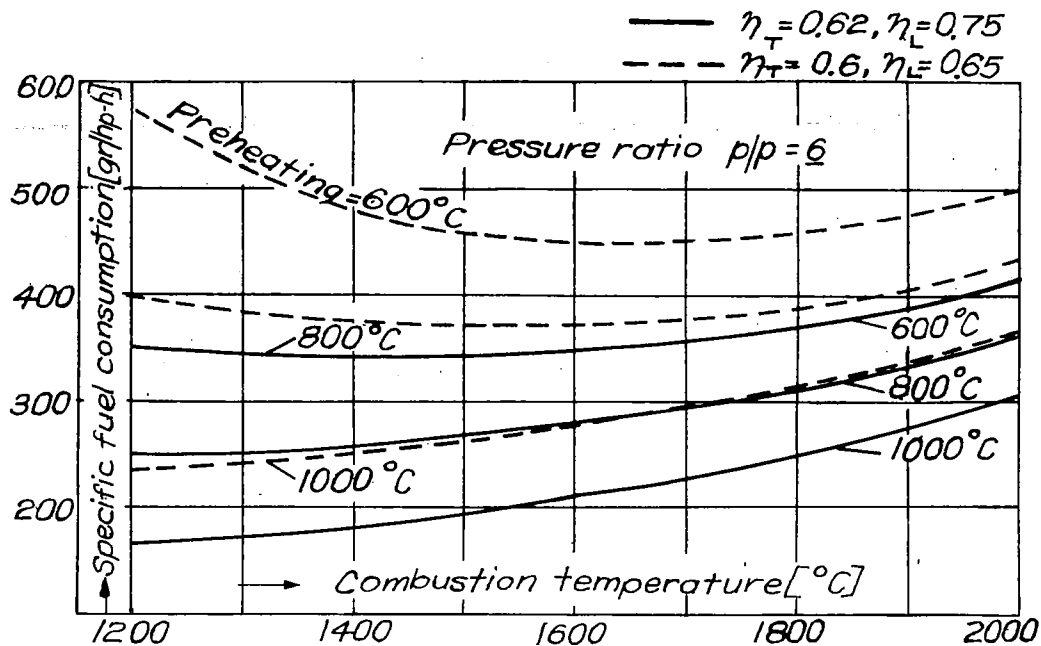


Figure 4.- Comparison of fuel consumptions between special power plant and Otto-engine for a pursuit plane with consideration of the radiator drag and the weight influence for equal surface loading.



Figures 5 and 6.- Specific fuel consumption of the gas turbine (gas oil) as a function of the combustion temperature for different preheating of air and efficiencies.

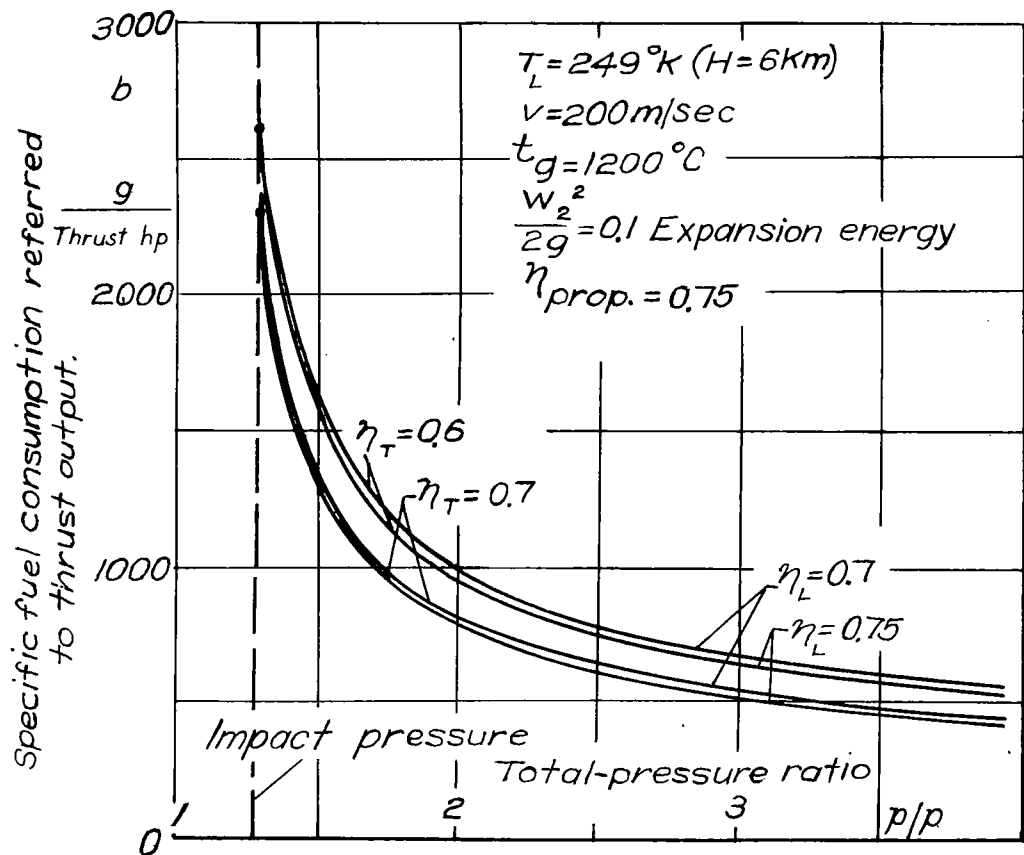


Figure 7.- Influence of the compression on the fuel consumption (power plant C).

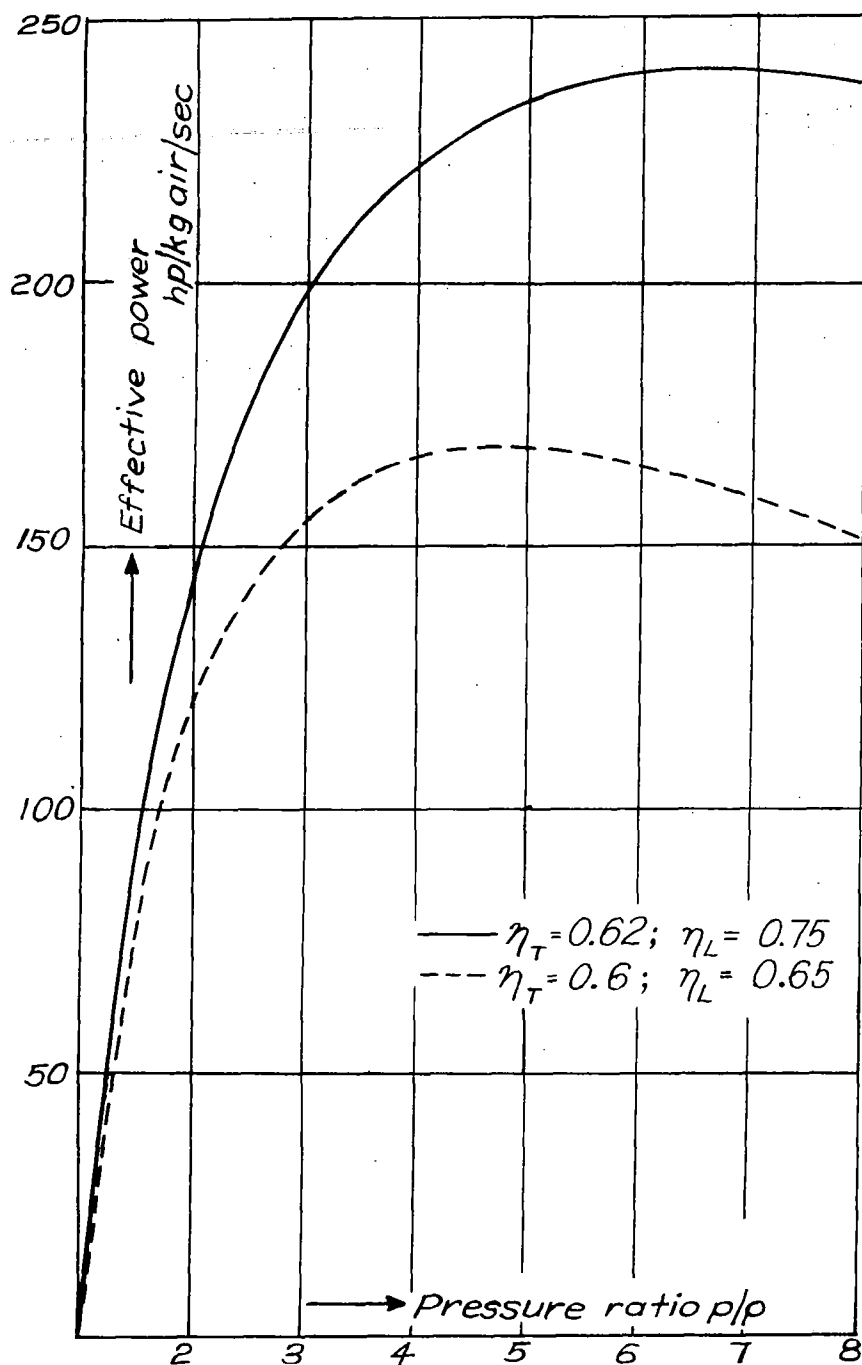


Figure 8.- Effective power of the gas turbine for 1 kg air/sec as a function of the pressure ratio p/p for different efficiencies and the combustion temperature $1400^{\circ}C$.

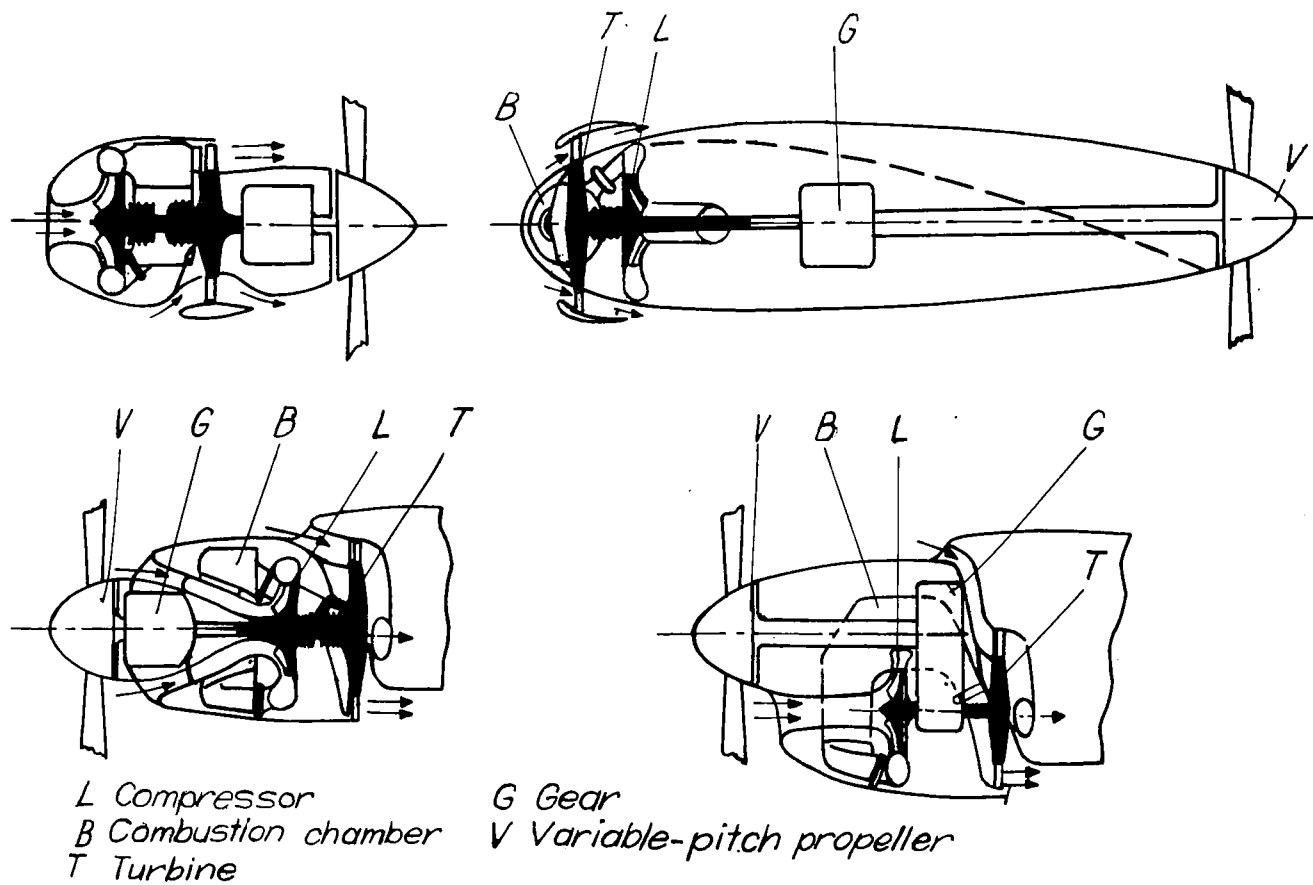


Figure 9.

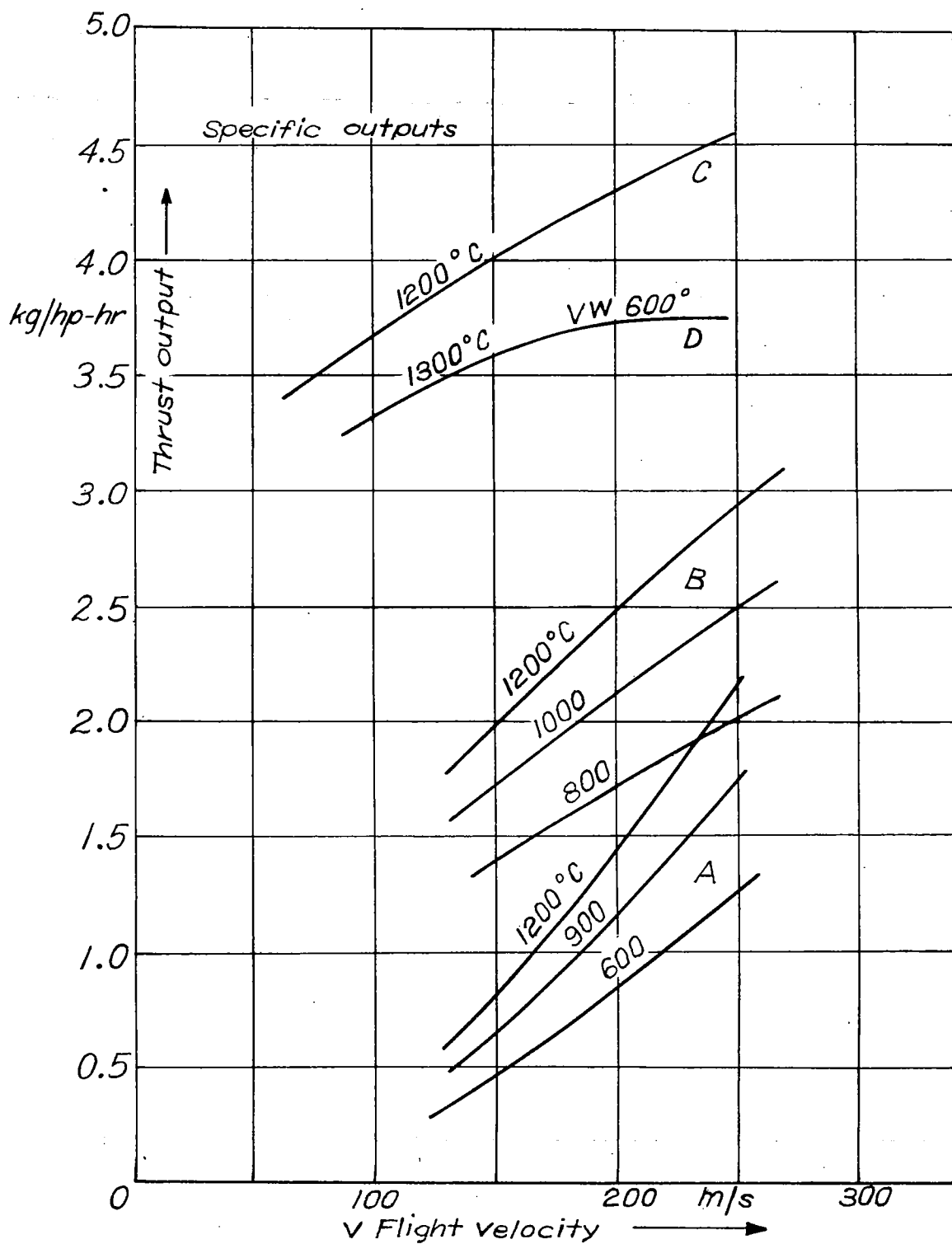


Figure 10.

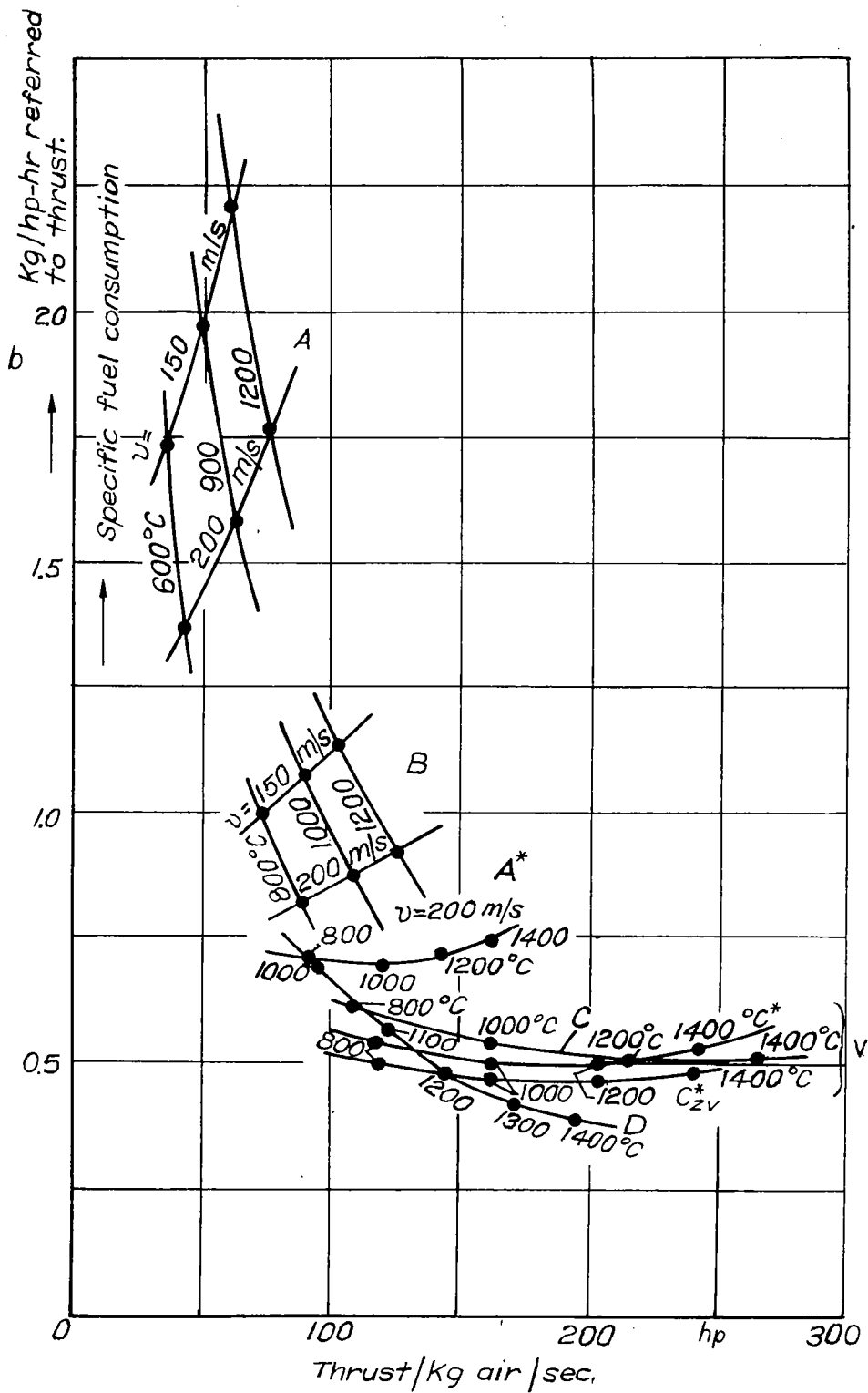


Figure 11.- Working range of various jet propulsion plants.

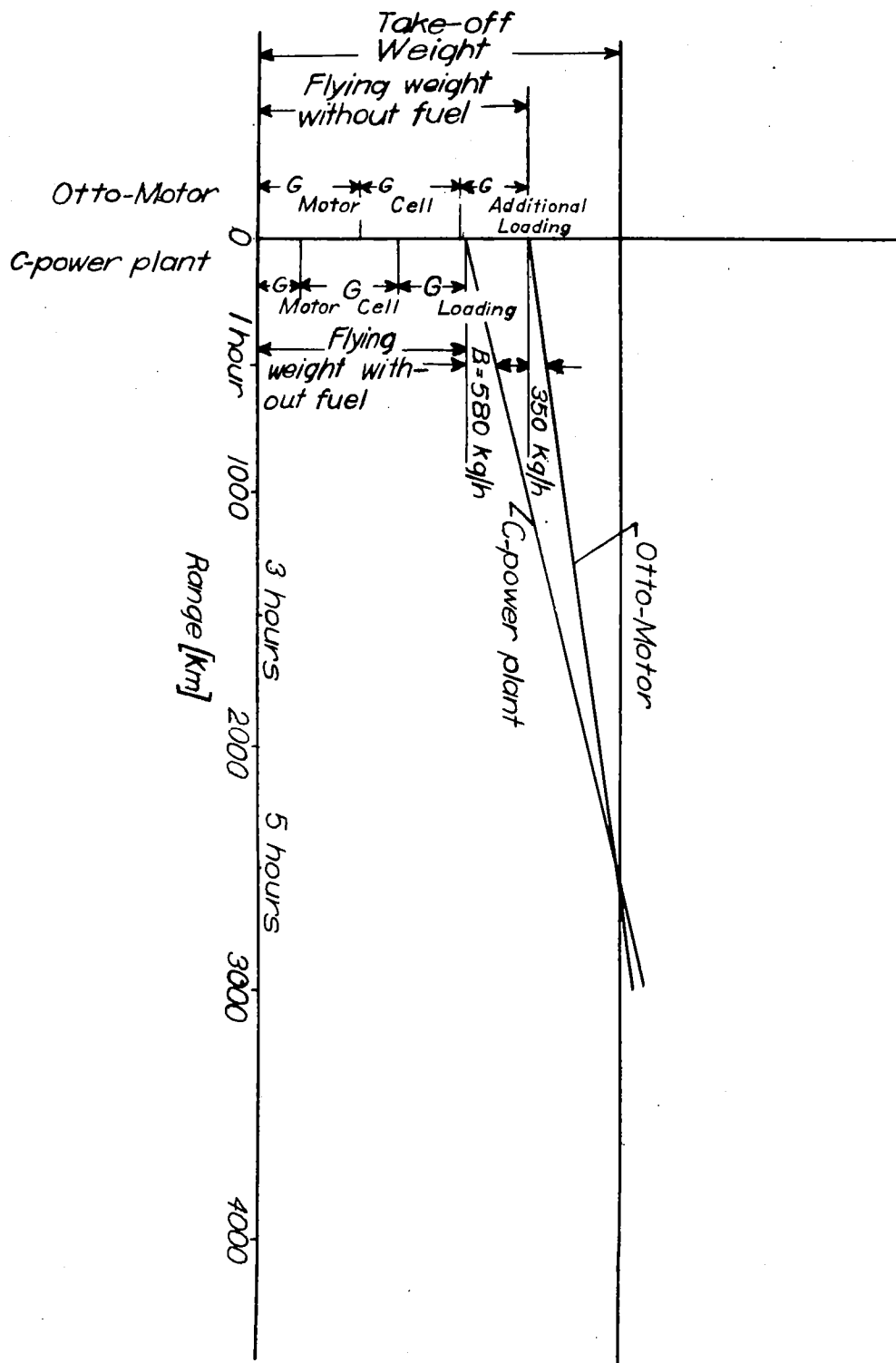


Figure 12.- Comparison of range between Otto motor and C power plant; flight altitude 6 km; velocity 500 km/h.

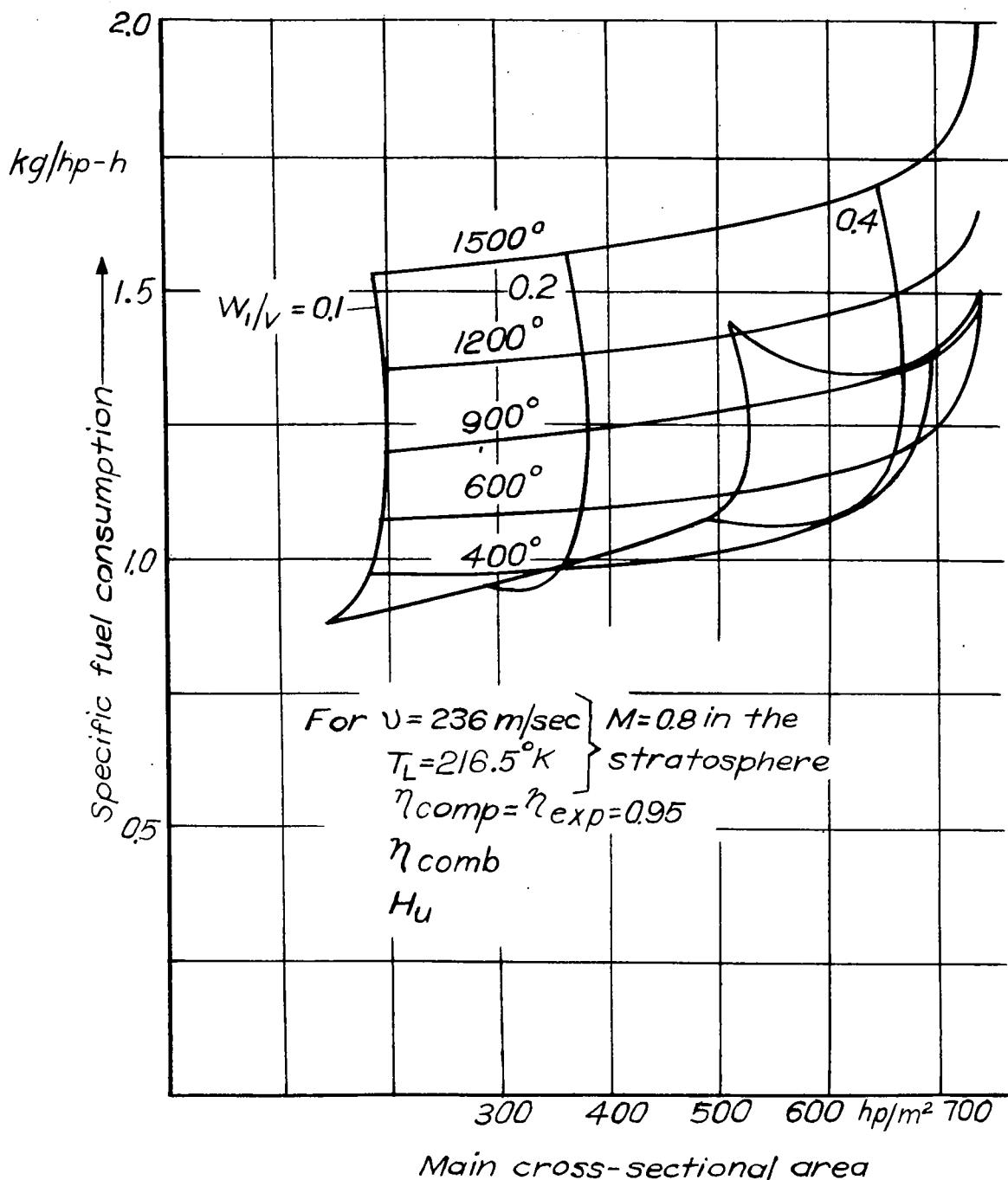


Figure 13.- Specific fuel consumption and main-bulkhead outputs at 11 km altitude.

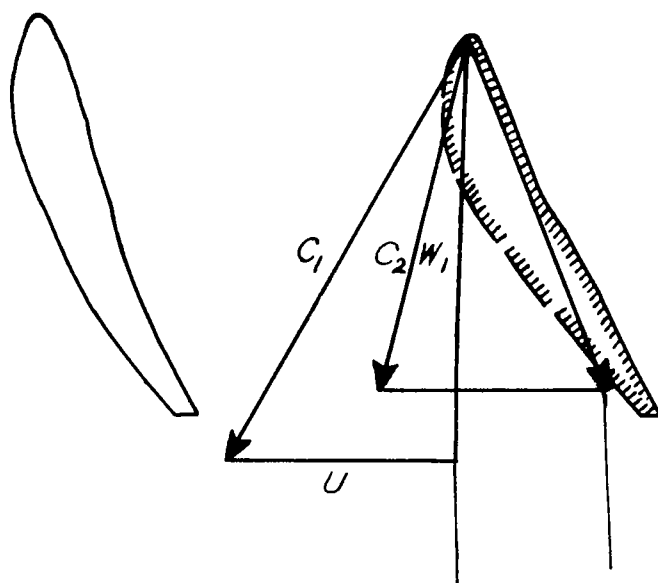


Figure 14.- Velocity triangles of B power plant.

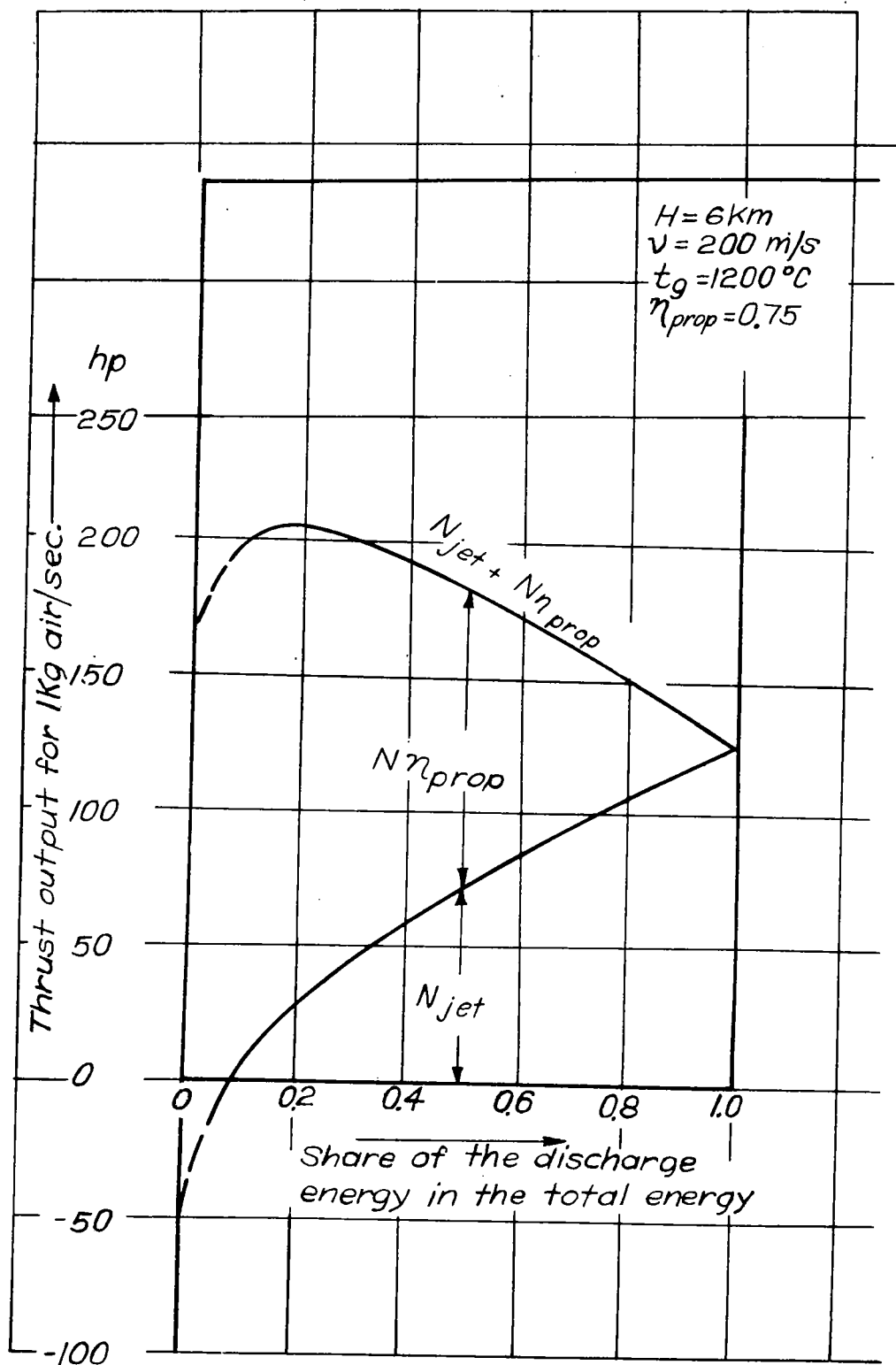


Figure 15.- Energy distribution between jet and propeller propulsion.

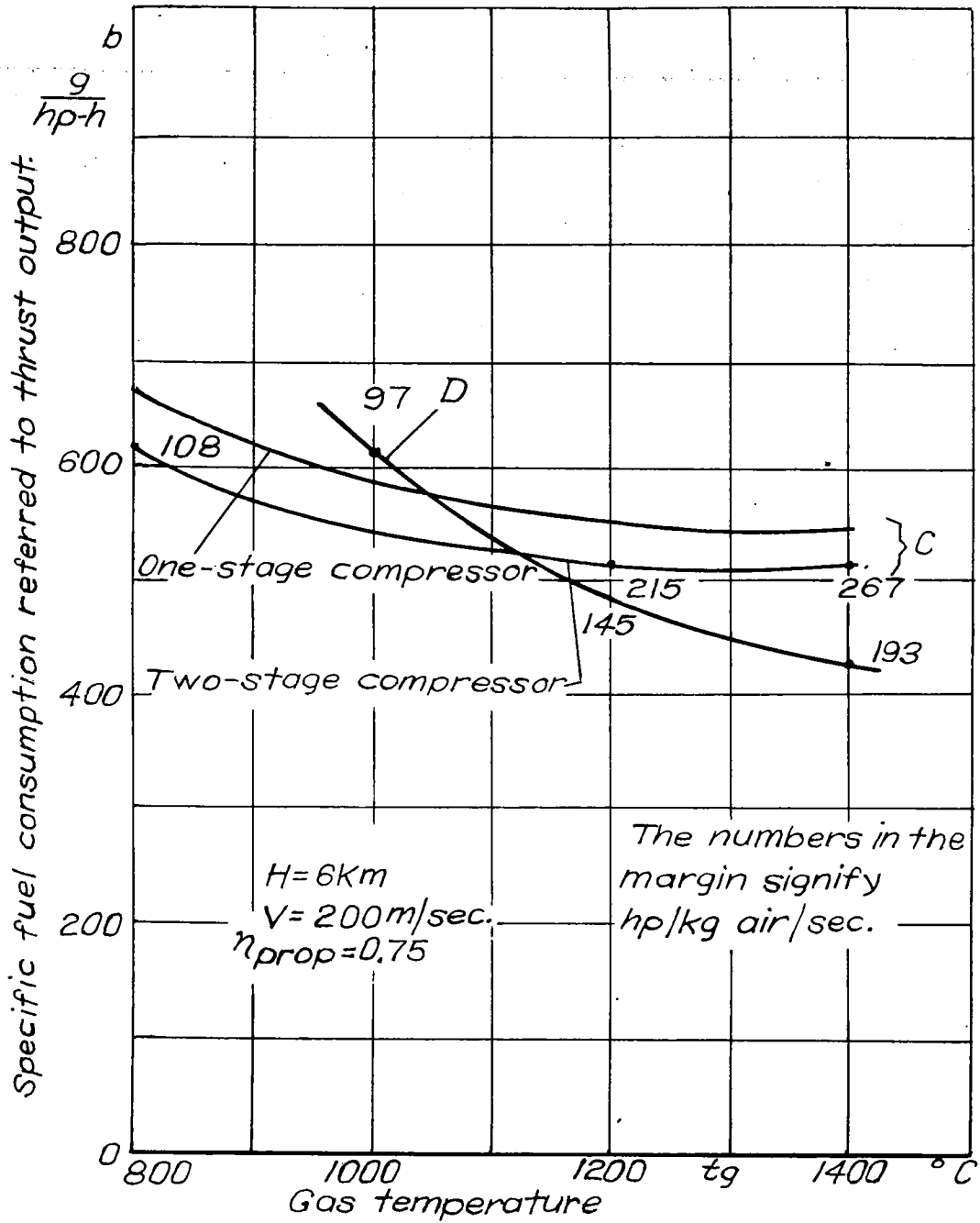


Figure 16.

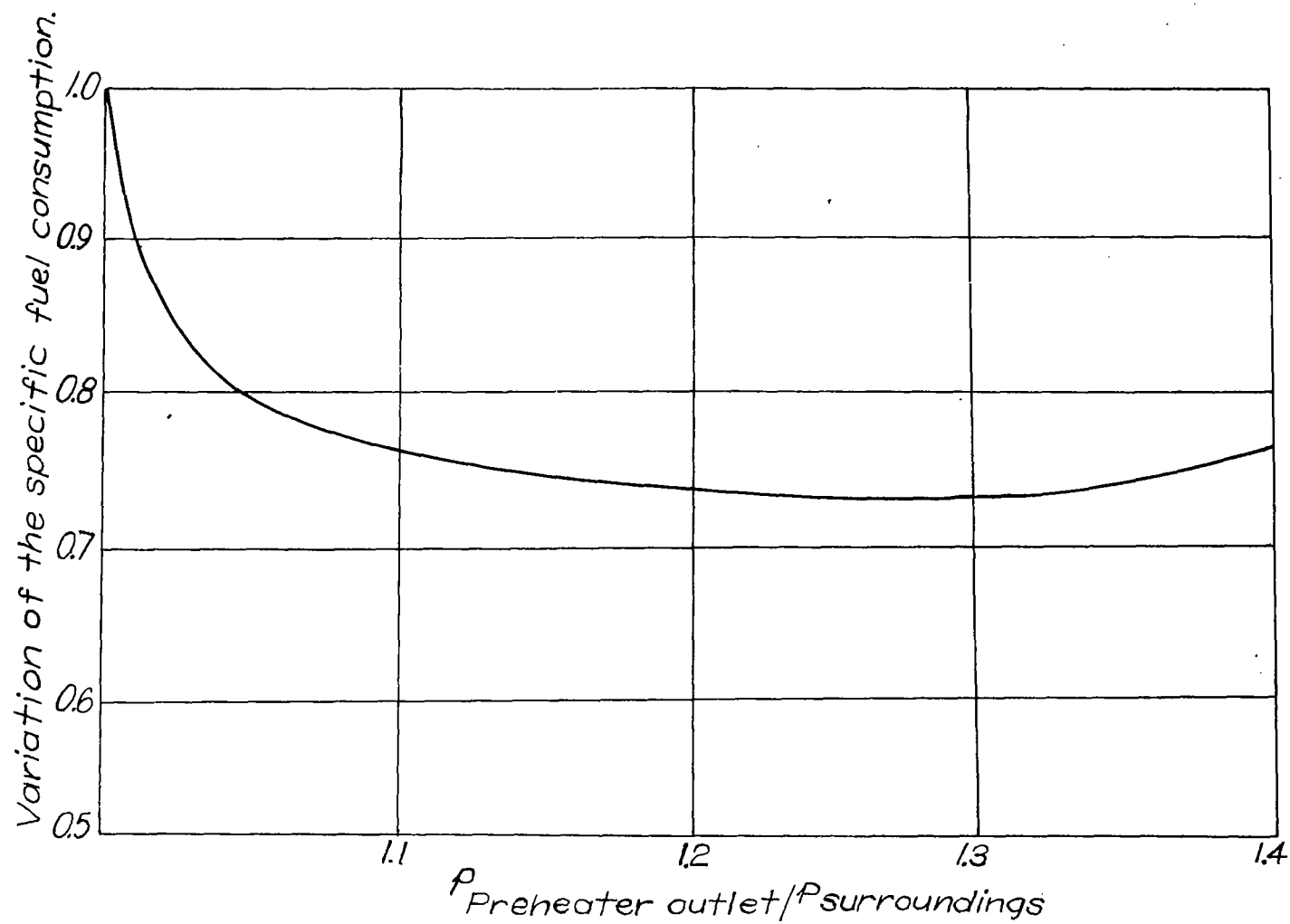


Figure 17.- Specific fuel consumption of the D power plant for energy distribution for turbine and jet.

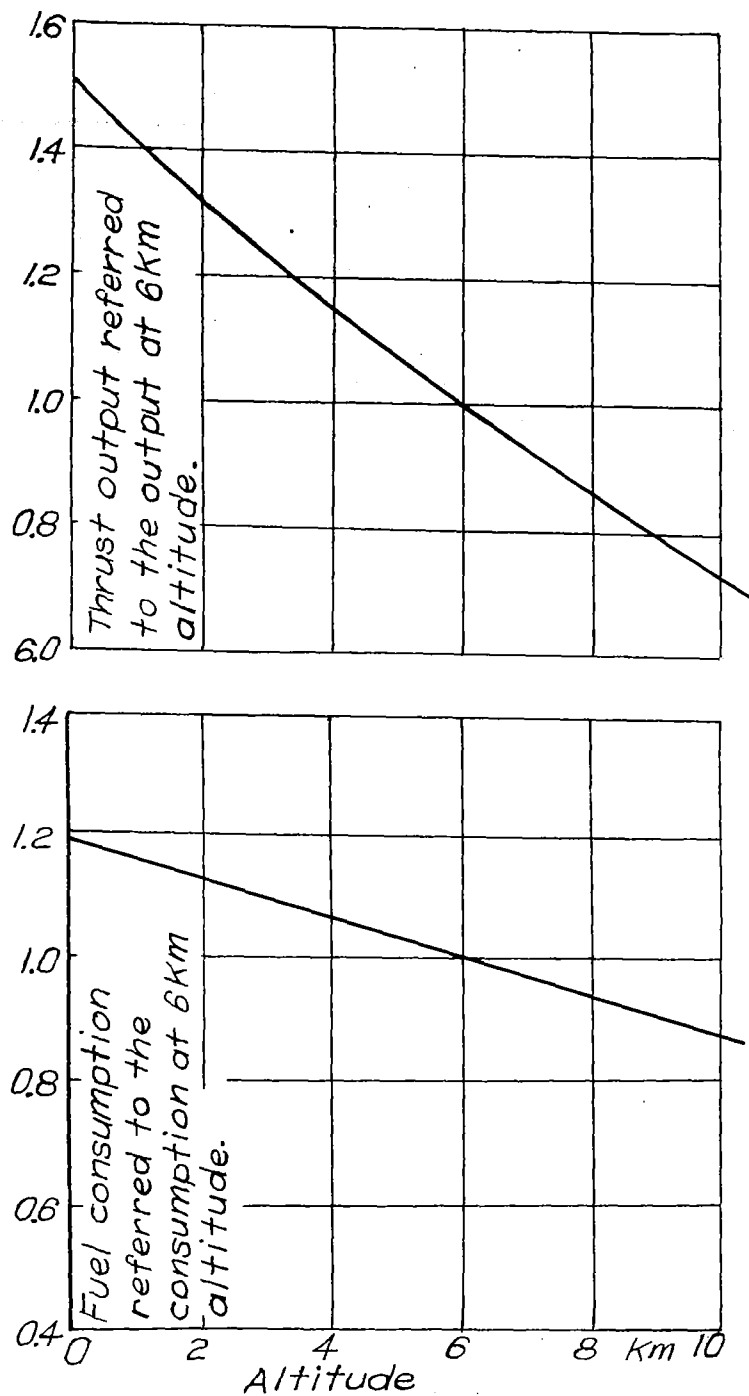


Figure 18.- Variation in output and fuel consumption of a C power plant at transition from 6 km flight altitude to other altitudes (flight speed = 200 m/s).

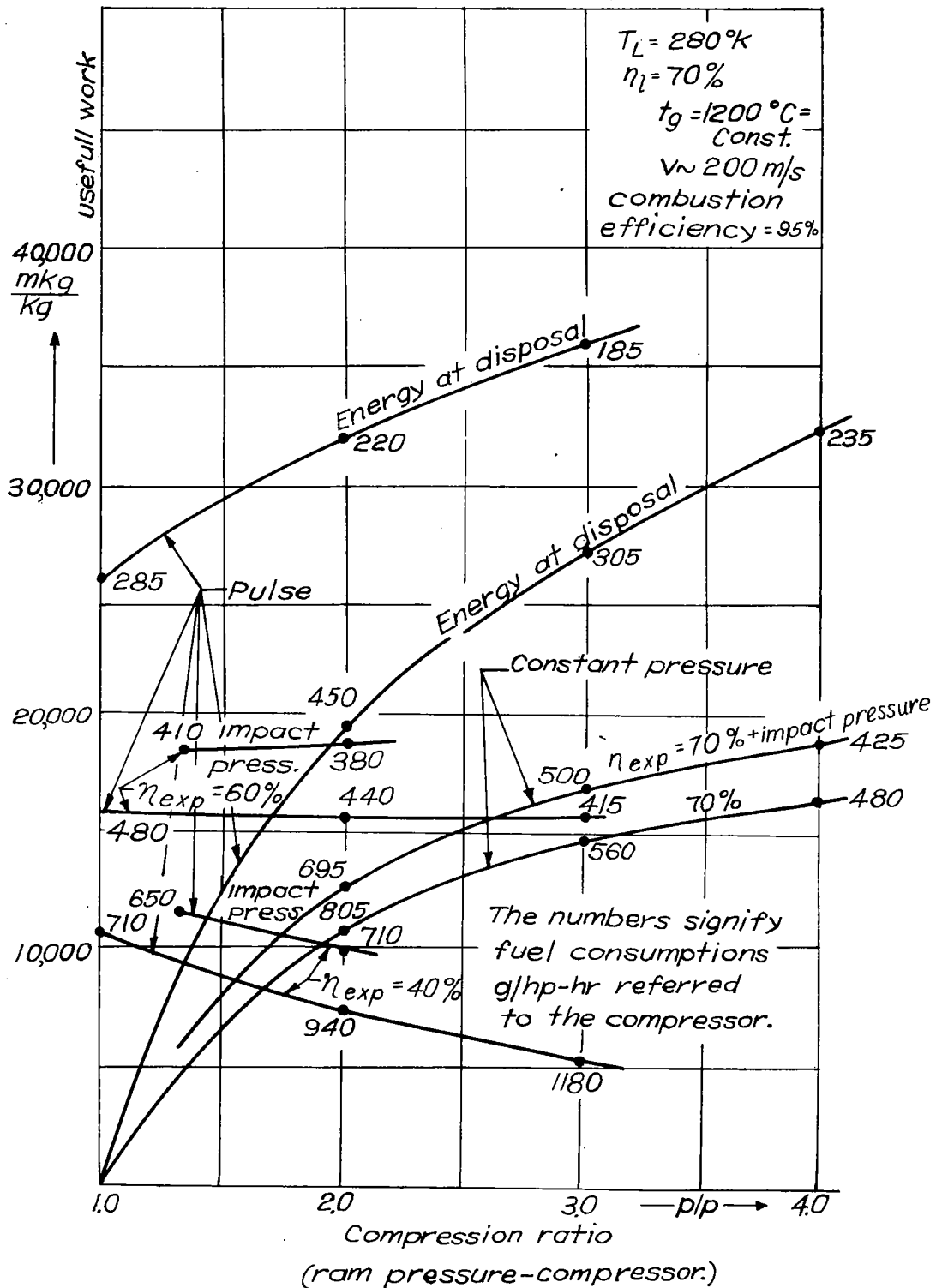


Figure 19.- Comparison of outputs between constant-pressure and pulse method.

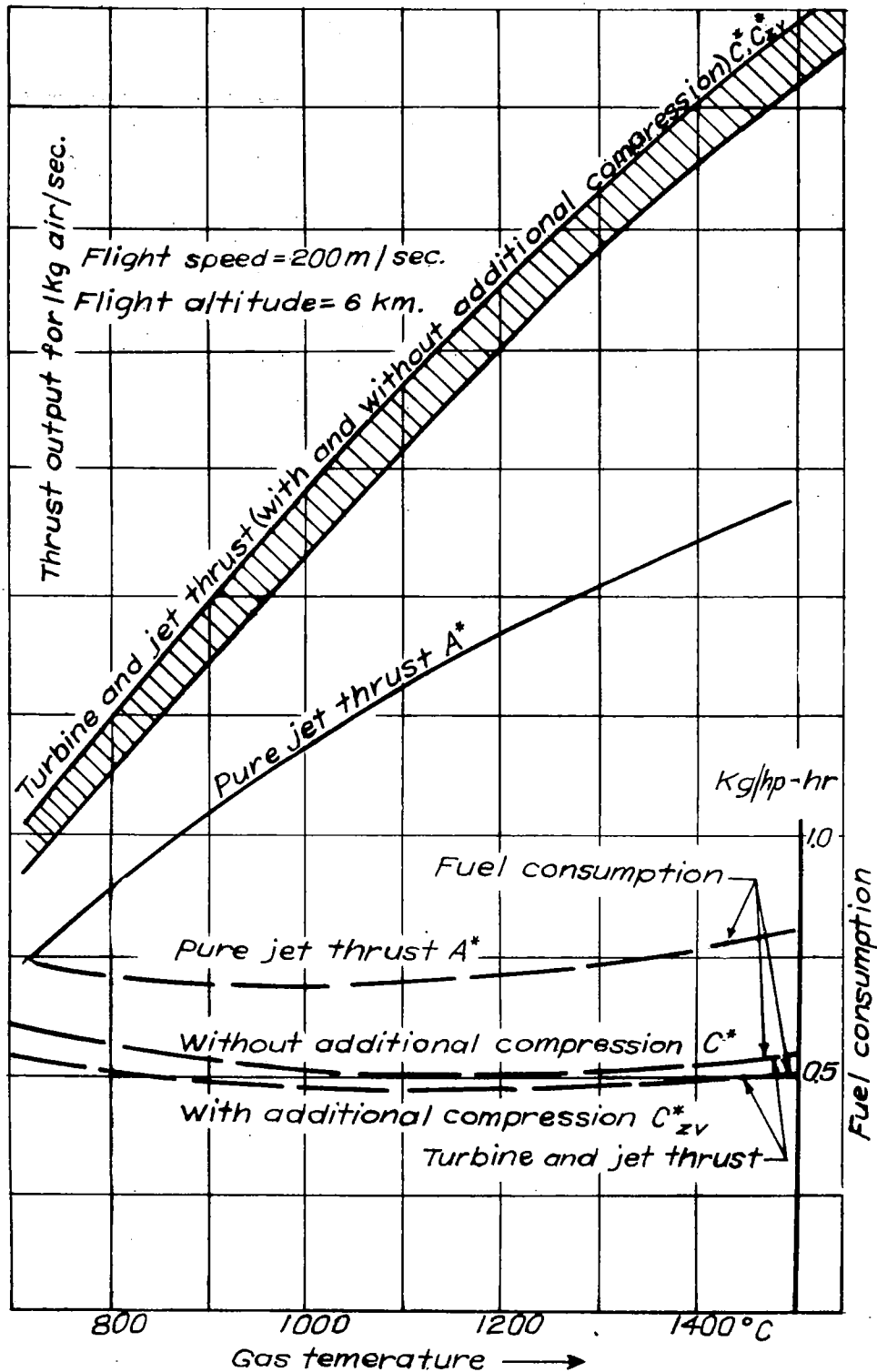


Figure 20.- Outputs and fuel consumption for the pulse method.

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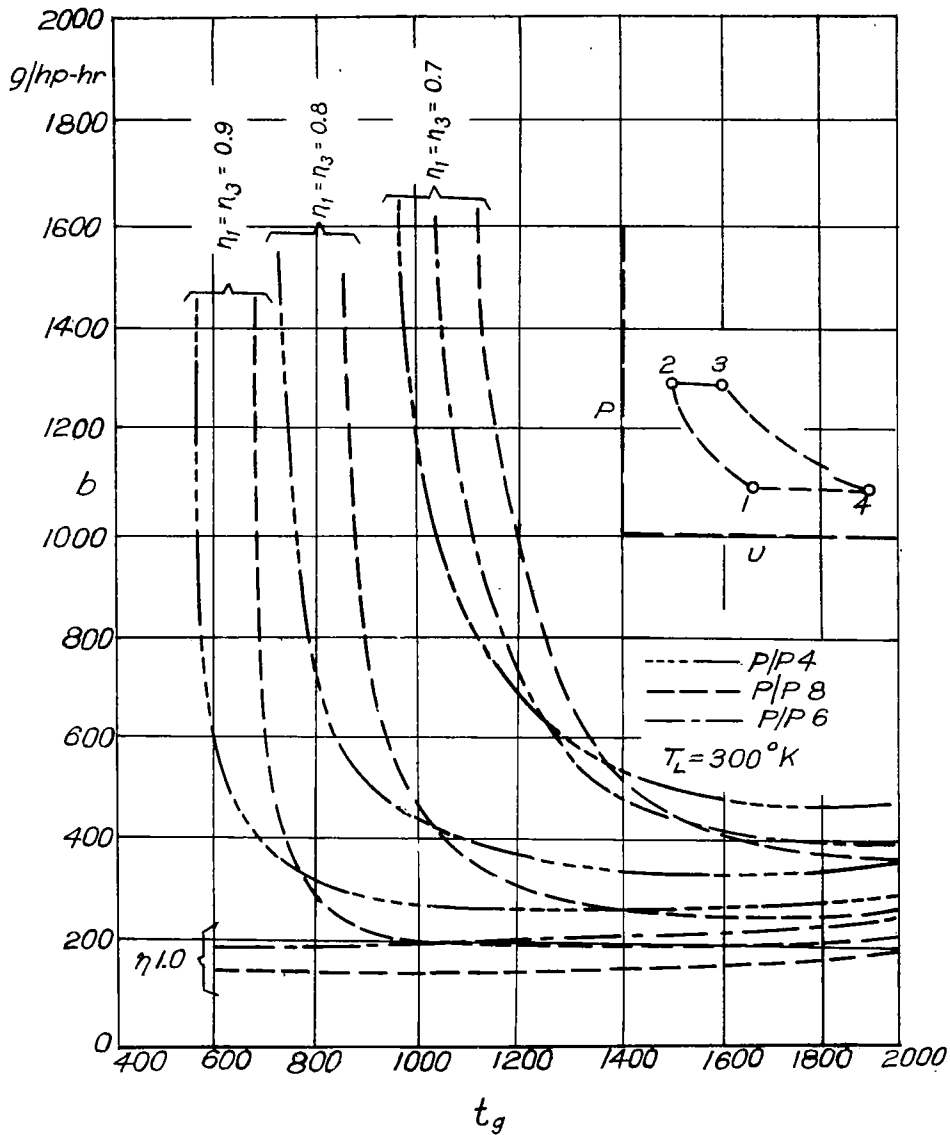


Figure 22.- (The legend for this figure was illegible in the only available copy of the original language version of this paper.)

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